Water Research Centre

Assessment and Management of Material Stability in Contemporary Environmental Guidelines for the Use and Disposal of Biosolids Products

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Acronyms

Acronym	Meaning
ANZECC	Australian and New Zealand Environment Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ATAD	Autothermal Thermophilic Aerobic Digestion
ATP	Adenosine Triphosphate
ATP	Adenosine Triphosphate
AUSPLUME,TAPM and CALPUFF	Air Pollution Models
AVSR	Additional Volatile Solids Reduction
BAS	Biosolids Assurance Scheme
BFP	belt filter press
BMP	Bio Methane Potential
BN	Bayes Nets
BOD	Biochemical Oxigen Demand
BOD	Biochemical Oxygen Demand
BRC	British Retail Consortium
BSI	British Standard Institution
BSI	British Standard Institution
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CBA	Cost Benefit Analysis
CCME	Canadian Council of Ministers of the Environment
COD	Chemical Oxygen Demand
COD	Chemical Oxygen Demand
COS	Carbonyl sulfide
CS2	Carbon disulfide
DALY	Disability-adjusted life year
DECWA	Department of Environment and Conservation of Western Australia
DEFRA	Department for Environment, Food and Rural Affairs
DMDS	Dimethyl disulfide
DMS	Dimethyl sulfide
DMTS	Dimethyl trisulfide
DOC	Dissolved Organic Carbon
DRI	Dynamic respiration index
DT	Detection Threshold
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. (German Association for Water, Wastewater and Waste)
EC	European Community
EDC	Endocrine Disrupting Compounds
EEC	European Economic Community
EMS	Environmental Management Systems
EPA	Environmental Protection Authority
EPS	Extracellular Polymeric Substances
ERA	Environmental Risk Assessment
FID	Flameionization detector

Acronym	Meaning
FPD	Flame photometric detector
FTA	Fault Tree Analysis
GC	Gas Chromatograph
GLC	Ground Level Concentration
HACCP	Hazard Analysis and Critical Control Points
HS	Headspace
ISO	International Organization for Standardization
ISO	International Organization for Standardization
KEDRF	Key Events Doseï Response Framework
LOI	Loss of Ignition
MCDA	Multicriteria Decision Analysis
MPN	Most probable Number
MS	Mass Spectrometer
MT	Methyl mercaptan
NBP	National Biosolids Partnership
NFSA	Norwegian Food Safety Authority
NHMRC	National Health and Medical Research Council
NRC	National Research Council
NRMMC	National Resource Management Ministerial Council
NSW	New South Wales
NWQMS	National Water Quality Management Strategy
ODP	Odour detection port
OEL	Occupational Exposure Limit
OFWAT	The Water Regulator for England and Wales
ORP	Oxidation Reduction Potential
OTV	Odour threshold value
OU	Odour Units
PAS	Publicly Available Specification
PAS	Publicly Available Specification
PID	Photoionization detector
PURE	Project on urban reduction of eutrophication
QMRA	Quantitative Microbial Risk Assessment
RBA	Residual Biological Activity
REVAQ	Renare Vatten ï Bättre Kretslopp (Cleaner Water - Better Recycling)
RT	Recognition Threshold
SEPP	State Environment Protection Policies
SFW	Solid food waste
SI	Sudden Increase
SOUR	Specific Oxygen Uptake Rate
SPME	Solid Phase Micro-Extraction
SRT	Sludge Retention Times
TD	Thermal desorption
TKN	Total Kjedhal Nitrogen
TMA	Trimethyl amine
TOC	Total Organic Carbon
TOC	Total Organic Carbon

Acronym	Meaning
TPAD	Temperature phase anaerobic digestion
TVOSC	Total Volatile Organic Sulphur Compounds
VAR	Vector Attraction Reduction
VFA	Volatile fatty acids
VOC	Volatile Organic Compounds
VSC	Volatile Sulphur Compounds
VSR	Volatile Solids Reduction
WAS	Waste Activated Sludge
WEF	Water Environment Foundation
WHO	World Health Organisation
WRC	UNSW Water Research Centre
WSOC	Water Soluble Organic Carbon
WWTP	Wastewater Treatment Plant

Glossary

Term	Explanation
Bayes Nets	ñA Bayesian Network consists of a directed acyclic graph of ónodesô and ólinksô that conceptualise a system. The values of the nodes are defined in terms of different, mutually exclusive, óstatesô (McCann et al, 2006). The relationships between nodes are described by conditional probability distributions that capture the dependences between variables.ö (Kragt, 2009)
Biosolids	Sewage sludge - The solid, semisolid, or liquid residue generated during the treatment of domestic sewage in a treatment works. Biosolids - The primarily organic solid product yielded by municipal wastewater treatment processes that can be beneficially recycled (whether or not they are currently being recycled) (USEPA) Sewage sludge that has been treated to meet the land-application standards in the Part 503 rule or any other equivalent land-application standards or practices. (US NRC 2002) ï see (Pepper et al., 2006)
EMS	Environmental Management System (see ISO 14000 series). The section of an overall management system that includes structure, planning activities, responsibilities, practices, procurements, processes and resources for developing, implementing, achieving, reviewing and maintaining an environmental policy.(Environment Protection and Heritage Council, 2006)
enHealth	ñThe enHealth Council, a subcommittee of the National Public Health Partnership, brings together top Environmental Health officials at the Federal and State/Territory level along with representation from the Australian Institute of Environmental Health, the environment and public health sectors, the Indigenous community and the wider community. The Council has the responsibility for providing national leadership, implementation of the National Environmental Health Strategy, forging partnerships with key players, and the development and coordination of advice on environmental health matters at a national level.ö (Department of Health and Aging, 2002)
Environmental Values	- (As applied to Environmental Values) ñValues are defined as prescriptive beliefs about end states of existence (e.g., peace) and modes of conduct (e.g., justice) that transcend specific objects and situations and that are held to be personally and socially preferable to opposite end states of existence (e.g., war) and modes of conduct (e.g., injustice) (Reser and Bentrupperbäumer, 2005) - Example of water : ñParticular values or uses (sometimes called beneficial uses) of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and that require protection from the effects of contaminants, waste discharges and deposits. Several Environmental Values may be designated for a specific water bodyò (Environment Protection and Heritage Council, 2006).
ERA	Environmental (Health) Risk Assessment. Covers Quantitative Microbial Risk Assessment. The Australian version of ISO 31010 refers to toxicological risk assessment reflecting ERA commonly being equated with chemical toxicity and carcinogenicity risk assessment.
HACCP	Hazard analysis and critical control points - A systematic, proactive, and preventive system for assuring product quality, HACCP and safety of processes by measuring and monitoring specific characteristics which are required to be within defined limits
HRA	See ERA
ISO	International Standards Organization (number designates standard and document within standard
ISO 14001 : 1996/2004 (Environmental Management Systems)	ñAn international accredited standard that provides a generic framework for guidance on the development and implementation of an environmental management system to minimise the impacts of business operations on the environment and to foster environmental sustainabilityò (NH&MRC, 2013)
MS	ISO 9000 Management Systems Standards - The ISO 9000 family of standards has been developed to assist organizations, of all types and sizes, to implement and

Term	Explanation
	operate effective quality management systems. The System approach to management involves identifying, understanding and managing interrelated processes as a system contributes to the organizationôs effectiveness and efficiency ¡n achieving its objectives. (ISO, 2005)
MTM Consortium	Monitoring Tailor Made Consortium ï group of European and US primarily water management scientists in the 1990s/2000s who worked increase the quality and efficiency of water quality monitoring
NH&MRC	National Health and Medical Research Council
NRMMC	Natural Resource Management Ministerial Council,
REQUAL	A Tool to Test Implementation of The Framework for Management of Recycled Water Quality and Use ï Essentially a Recycled Water Quality management guidance system developed for the Water Services Association of Australian
Risk	ñEffect of uncertainty on objectivesò (ISO, 2009) NOTE 1 An effect is a deviation from the expected positive and/or negative. NOTE 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process). NOTE 3 Risk is often characterized by reference to potential events (2.17) and consequences (2.18), or a combination of these. NOTE 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood (2.19) of occurrence.
Risk Management	ñCoordinated activities to direct and control an organization with regard to riskò (ISO, 2009)
Risk uncertainty	ñUncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihoodé Risk management explicitly takes account of uncertainty, the nature of that uncertainty, and how it can be addressed.ò (ISO, 2009)
Vermin	Animal pests attracted to biosolids viewed as potential disease vectors and nuisances mainly diptera (flies) and rodents.

Executive summary

The New South Wales (NSW) Environmental Guidelines for the Use and Disposal of Biosolids Products were released in 1997 to regulate the management of biosolids in the State. This document established different stabilisation grades (A, B and C) to be achieved by meeting a combination of estimated pathogen reductions, via stabilisation processes in the case of Grade B products, and verified pathogen reductions reflecting time and temperature for Grade A products. At the same time, all Grades need to meet concurrently at least one Vector Attraction Reduction (VAR) requirement and ensure none of the stabilisation grades exhibit offensive odours.

This document presents a review of biosolids stability and odour management issue using different data sources especially the scientific literature, industry reports, environmental legislation and personal communications. The goal of the Water Research Centre (WRC) team has been to provide evidence based recommendations in relation to biosolids management taking into consideration; the current understanding and operationalisation of the concept in Australia and around the world, how stability is measured and ensured, its relationship with odour and finally, how odour and stability might fit into risk and environmental management frameworks so it could be incorporated within revised guidelines.

A key task to understand was describe and refine understanding of biosolids stabilisation ï the irreversible changes associated with the processing of raw sludge. Aerobic digestion, anaerobic digestion and composting can be considered as true stabilisation processes. Alkali addition and thermal drying remove pathogens but do not yield a fully stabilised product which has major implications for further transport and processing. The literature indicates that there has been no agreement on a universal definition of stability and that óstabilityô needs to be defined for each process/transport/storage/reuse combination.

Review of approaches to biosolids stability management

At the national level it was found that NSW could be lagging behind their national counterparts on ensuring the production of stable products due to the lack of minimum operational conditions in the current biosolids guidelines. The evidence indicates that the stability criteria included in Biosolids Guidelines in Australia ï at the National and State level ï can be characterised as follows:

- The stability grading has been replaced in some jurisdictions by a ñpathogenò or ñtreatmentò grading. However, all of them use the same stabilisation processes as the NSW guidelines (anaerobic and aerobic digestion, lime stabilisation, composting and air drying).

- In the National and Western Australia (WA) guidelines the VAR measures are combined with the treatment conditions to create the ñpathogen grading classificationò. In Victoria (VIC) and South Australia (SA) a similar approach to NSW is used, that is, a separate table for the VAR measures.
- The requirements needed to grade biosolids at a specific level of stability quality are more restrictive in the National, WA and VIC guidelines than in the NSW guidelines, especially for products with a similar classification to class B biosolids. The inclusion of Sludge Retention Time (SRT) requirements in anaerobic digestion and the microbiological verification of performance for approved processes in other states are examples of this. SA guidelines present similar conditions to NSW with some modifications catering for their practices at Bolivar Wastewater Treatment Plant.
- There are more than one quality grade between the untreated biosolids and the top quality biosolids product in some jurisdictions. For example, the National and more recent WA guidelines have P2 and P3 classifications, which are similar to a Stabilisation Grade B in NSW.
- The requirements for top quality biosolids, which can be used without restrictions, are similar in all the guidelines.

When compared against their international peers the single most relevant finding in relation to stability is the lack of a óbest practice manualô for the management of biosolids in NSW. As illustrated by the 2005 US National Biosolids Partnership manual a óbest practice manualô could include a range of process recommendations to ensure a stable product, or could take the form of a risk based management tool such as Hazard Analysis and Critical Control Points (HACCP) which could be also used to manage the risks associated with pathogens and contaminants.

The number of programs associated with best practices in the management of biosolids, including those associated with stability continues to grow around the world. These programs support the existing legislation in countries such as the United Kingdom (UK), Sweden and the United States (US) and promote the benefits of biosolids beneficial reuse and reduce the risk of potential óoutrage episodesô associated with poorly stabilised biosolids, which are recognised as the biggest threat to biosolids beneficial reuse programs. Beyond these óBest Practice Programsô, a growing number of certification schemes were also found in overseas countries such as the Renare Vatten ï Bättre Kretslopp (ReVAQ)® certification in Sweden and the Biosolids Assurance Scheme (BAS) in the UK.

Overseas experiences show that the different approaches taken to the management of stability in biosolids are based on environmental, economic, social and legal constraints found in each country. The policies and practices analysed in this review show the potential pathways for NSW in relation to encouraging application of high quality biosolids to agricultural land (Norway), the use of a mixed approach via incineration/agricultural usage Germany, Denmark) or the production of "bio-soils" (Finland).

Restrictions on contaminant concentrations in sludge are tightening, especially in Europe, making it almost impossible in some countries to beneficially reuse biosolids on agricultural land unless all the potential contaminants upstream of the wastewater treatment plant are controlled. At the same time, there is an increasing level of interest worldwide in recycling phosphorus through the beneficial reuse of biosolids which requires merging pathogen, contaminant and odour dimensions of biosolids processing under a coherent risk management framework.

What is stabilisation?

The current operational definition of stability (Grade A or B) in the NSW guidelines is in effect the two different expected qualities in the final biosolids product:

- Sanitisation or hygienisation (for grade A)
- Reduction of pathogens and putrefaction (for grade B)

Grade A deals with pathogens exclusively and it is considered outside the scope of this report. Different stabilisation processes are able to reduce pathogens but this is different to reducing putrefaction by transforming the organic matter present in the raw sludge. In this report, we focus on Grade B approved processes and the associated Vector Attraction Reduction (VAR) measures included in the Biosolids Guidelines (NSW EPA, 1997) due to the fact that the large majority of biosolids products in NSW are considered grade B (PSD, 2015).

This definition is however insufficient as achieving VAR does not mean stability has been achieved, rather achieving stability will achieve VAR (WEF, 2012). Accordingly we have reviewed the suitability of each of the stabilisation processes and the assessment methods with a focus on the VAR measures presented in the NSW Biosolids Guidelines. The irreversible/reversible nature of each 'stabilisation' process and its contribution in moving the raw sewage sludge towards 'inertness' present a potential criterion to judge their suitability in ensuring the stability of biosolids. The protocols and thresholds associated with VAR in the current guidelines appear to be relevant to the operation of each stabilisation process to ensure pathogen reduction but they don't guarantee a product free of offensive odours. They need to be **complemented** with better operational process controls or óminimum standardsô on processing which need to be validated by the EPA. Similarly, additional or new measurements need to be considered to determine the óstabilityô of a biosolids product.

For irreversible stabilisation processes such as anaerobic and aerobic digestion, minimum sludge retention times (SRT) need to be incorporated in the updated guidelines to reduce the risk of further nuisance odour generation in the digested sludge due to operational constraints. The assessment of óstabilityô needs to be done after dewatering, conveying and storage to account for the potentially adverse effects of these practices on óstabilisedô biosolids. The current VSR threshold for aerobic and anaerobic digestion is a relative operational measurement easily achieved by the wastewater treatment plants (WWTPs). As it is very specific to the context of each site, it provides little information on the appropriateness of the biosolids product for its intended use. A potential way forward is to use volatile solids (VS) brackets to classify biosolids products stabilised using aerobic and anaerobic digestion in a similar way as it is practiced in Germany. In composting, temperature and time control need to be supplemented with the use of CO_2 evolution and the incorporation of the current composting standards AS 4454-2012 into the drafting of the new biosolids guidelines seems appropriate.

For those reversible stabilisation processes such as alkali addition and thermal drying some changes are warranted. First of all, they need to be considered non-stabilisation processes with an important role to play in the State. Alkali addition needs to be kept as a feasible emergency pathway to dispose of biosolids when irreversible stabilisation processes are unavailable and the VAR measures associated with alkali addition need to be upgraded to the national standards. Thermal drying should be considered as a potential route if the sludge has been anaerobically or aerobically stabilised previously unless incineration is feasible.

Odour emissions from biosolids and links to stabilisation

Types of odorants emitted from biosolids depend on the stabilisation methods used. However, most emissions typically consist of volatile sulfur compounds, ammonia and other compounds produced from the degradation of organic matter. These odorants can be perceived at low concentrations and have largely offensive odour characters ranging from rotten eggs, rotten vegetables and garbage to rotten fish and ammonia.

As odours are produced from the degradation of organic matter, therefore a more stable product implies less odours produced. Current stabilisation guidelines have been developed to satisfy microbial and vector attraction requirements, while odour emissions are explicitly linked to both of these levels, further stabilisation may be required to meet an odour acceptable product, being closely linked to the definition of stabilisation itself, as the case of limited change. A limitation of the current guidelines is that odour itself is not a specific measure. While the current guidelines require Grade B biosolids to ñnot exhibit offensive odoursò, what is classified as an offensive odour is not established.

Methods of evaluating odour quality can use analytical (odorant concentrations) or sensorial methods (how people perceive odours). A combination of both of these is recommended.

- Concentrations of key odorants emitted from biosolids could be monitored analytically using standardised sampling methods. Typical odorants typical for each stabilisation method would need to be lower than a certain level for different biosolids applications.
- Taking a sensorial approach, intensity, hedonic tone and odour character of the biosolids product could be used onsite as part of regular performance monitoring, these measures are better indicators of nuisance emissions compared to odour concentration. These can be assessed using the Odour profiling method (OPM), similar to the 2170 Flavour Profile Analysis method from ñStandard Methods for the Examination of Water and Wastewaterò.

The classification of biosolids emissions into categories depending on odour properties (sensorial and/or analytical) could be used to inform suitable biosolids re-use options. Suitable thresholds for biosolids odour quality categories would need to be developed with consultation with utilities, community and regulators.

The final product stability can also be tested by residual biodegradability tests, however the effect of downstream processing needs to be considered. For example the tests could be carried out on the dewatered cake or after conveying to understand the contribution of these processes or to predict the odour potential of the product. Options include Specific Oxygen Uptake Rate (SOUR) for aerobic digestion and Biochemical Methane Potential (BMP) for anaerobically digested solids which are included in the current guidelines. Another option is measuring labile protein content in the final product, as labile proteins are precursors to odorous volatile sulfur compounds.

In parallel with the adoption of odour quality and stability requirements of the biosolids product, certain operational targets for each stabilisation method should be established, which will help utilities meet biosolids odour quality, without being overly prescriptive. For example, longer SRTs are recommended to reduce odour potential; however digester efficiency and the effect of downstream processing on odour emissions also need to be considered. The guidelines should suggest additional techniques to meet required odour quality based on the underlying microbial and chemical processes occurring in each stabilisation process. For example, minimising shear during dewatering and conveying can improve biosolids odour quality and handling properties. This approach will allow more flexibility between sites, allowing utilities to treat their biosolids to levels suitable to their end use, taking into account site specific factors and existing infrastructure.

The approach to monitoring of odour quality and other performance parameters throughout biosolids processing can also be informed by risk management approaches.

Risk and Environmental Systems management frameworks

In the original biosolids management guidelines it was stated: *“These guidelines are a step towards producing revised guidelines based on risk assessment.”* (NSW EPA, 1997) Reflecting this aim, this review outlines findings, conclusions and recommendations on the applicability of risk assessment and environmental management principles to odour, stability and vermin management. It focuses on Risk Management (RM) and Environmental Management Systems (EMSs) and identifies key documents reviewed and conclusions reached.

We first asked the question to what extent odour analysis and management could fit into a risk assessment and management paradigm? As with water, odour impact analysis seemed fully amenable to risk management tool application. The extent odours constitute a health risk depends greatly on the population under consideration and the odorant concentration. However the ISO 31000 meaning of the word óriskô can cover odours being unacceptable or otherwise for other reasons because the definition of óriskô is general rather than human health specific: *“Effect of uncertainty on objectives” (ISO, 2009).*

A range of risk assessment tools were identified for managing odour risk, notably cause X consequence risk matrix, Environmental risk analysis, HACCP and Fault Tree analysis. To accommodate the use of these tools the use of Environmental Management Systems is proposed in order to provide an overall framework for their application and ensure that institutional arrangements for biosolids management are sound.

The concept of biosolids óstabilityô has long been a vexed issue. A risk management perspective may however offer a solution to defining the concept of stability ï the application of HACCP which was originally developed for managing foods. Food production appears sufficiently analogous to biosolids production and management. If this is accepted then we suggest by analogy that óStableô biosolids be viewed as a short hand for: *Any biosolids intermediate or final product which is within specification for the proposed or existing, generation to recycling, process train and the applicable critical control point, as determined by objective measurements (e.g. chemical analysis, physical observation).* This proposed definition is designed to cover biosolids at intermediate stages along the biosolids production and management train as well as end products. A complementary way of defining it is *"Stability in biosolids is an irreversible and consistent low rate of biological activity achieved after adequate processing of sewage sludge".*

A suggested model for new guidelines which would allow the integration of EMS principles, RM techniques with the range of practical and technical methods already developed e.g. within the 1997 guidelines, is the latest Australian Drinking Water Quality guidelines which incorporates all these features. It is also suggested that the guidelines provide direction of the development and use of conceptual and mechanistic models.

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1. Introduction

The New South Wales Environmental Protection Authority (NSW EPA) has requested the development of a comprehensive review of the biosolids requirements included in the current NSW EPA Environmental Guidelines for the Use and Disposal of Biosolids Products (NSW EPA, 1997), focusing on material stability. The stabilisation grade included in the current NSW EPA Guidelines describes the quality of a biosolids product based on the level of pathogen reduction, vector attraction reduction and odour reduction.

The first descriptor for material stability is associated with the use of any of the following ñpathogen reduction processesò anaerobic digestion, aerobic digestion, air-drying, composting, lime stabilisation, extended aeration or other processes accepted by the NSW EPA to ensure a Grade B quality level is achieved. In addition, for Grade A the effectiveness of the process needs to be verified through microbiological means. Considerable research on the adequacy of current technologies to ensure stability from a microbiological perspective has been undertaken since the publication of the NSW guidelines. For example, (Sidhu and Toze, 2009) provides updated data on pathogen inactivation for aerobic stabilisation, anaerobic digestion, composting, air drying and lime stabilisation. This descriptor is considered to be outside the scope of the present report because it will be included in the parallel pathogen review.

The second descriptor for material stability is fulfilling of at least one of the Vector Attraction Reduction (VAR) requirements for any stabilisation grade A or B product. There are clear ôthresholdsô in the guidelines in relation to the VAR measures and the underlying evidence for their development deals simultaneously with microbiological and process/biochemical perspectives to ensure an adequate performance of the stabilisation processes included in the guidelines. For example, if the sewage sludge is treated using lime, the VAR relates to pH control to reduce pathogens in the sludge but if it is treated using anaerobic digestion the VAR relates to volatile solids reduction (VSR) to reduce the potential of further putrefaction of the digestate. The use of different perspectives as part of VAR measures, microbiological vs.process/biochemical, has contributed to the complexity of developing a universal definition of stability.

The third and last descriptor for a product classified as stable relates to odour reduction. In contrast to pathogen and vector attraction reduction, the current guidelines provide very few details on how this could be achieved but it clearly indicates that both product grades (A and B) *“...should not exhibit offensive odours” .* The nature of odour as being the physiological impact of certain compounds means methods of standardising and representing such impacts are difficult but nonetheless crucial for the success and continuity of the beneficial reuse of biosolids in NSW. The majority of the odorants emitted from biosolids are associated with the degradation of organic matter. For example, the degradation of proteins in the biosolids has been linked to the production of volatile sulphur compounds, ammonia, trimethylamine and a range of aromatic compounds (Rosenfeld et al., 2001a, Chen et al., 2004, Adams, 2003).

The production and emission of offensive odours from biosolids have been directly linked to the performance of stabilisation processes, such as anaerobic and aerobic digestion, as well as the way sludge is treated upstream and downstream of those stabilisation processes (Adams, 2004). For example, a range of factors, including onsite storage duration, conveying length, sludge pre-treatment, digester set-up, dewatering method, sludge blanket depth and chemical dosing have been linked in the literature to affecting the resultant biosolids odour emissions (Gabriel et al., 2005, Chen et al., 2007, Adams et al., 2007, Johnston et al., 2009, Kacker et al., 2011, Kim et al., 2011a, Murthy et al., 2009, Murthy et al., 2002, Novak et al., 2007).

Since the introduction of the US Environmental Protection Authority (EPA) 40CRF503 rule in 1993 and the publication of the NSW EPA guidelines in 1997 different reviews of biosolids management guidelines have been undertaken at the national level, including Western Australia, South Australia and Victoria, and at the international level including the United States (US) and different countries in Europe. Overall, two approaches have emerged, a risk-based approach similar to the current NSW guidelines, inspired by the work undertaken by the EPA in the US, and a more precautionary approach, inspired by the decision taken by some regulatory bodies in Europe in response to the uncertainty associated with the negative impact of contaminants present in the sludge.

The issues presented before, the use of different descriptors to define stability, the microbiological and process/biochemical perspectives used to define VAR measures, the complexity associated with an effective management of odour emissions and the contrasts of using a risk based versus a precautionary approach are fused in the concept of material stability. The WRC team has reviewed the literature on biosolids material stability from these perspectives and this report aims to present a comprehensive picture of the state of the art on this topic and at the same time shed some light on how odour and stability might fit into a risk and management framework so it could be incorporated within ñrevised guidelines based on risk assessmentò (NSW EPA, 1997). In short this review aims to answer the following questions:

1. What is stability in biosolids and how is it managed in Australia and around the world?

2. Are the current stabilisation processes and analytical protocols included in the NSW biosolids guidelines enough to produce a stable product?
3. Which are the links between stability and offensive odours associated with biosolids products?
4. Can the existing Australian recycled and potable water risk management frameworks be adapted to manage the risk associated with biosolids stability in NSW?

2. Material Stability

2.1. Chapter summary

The key point to understand stability lies in the irreversibility of the changes associated with the processing of raw sludge. Aerobic digestion, anaerobic digestion and composting can be considered as true stabilisation processes. Alkali addition and drying remove pathogens but leave the underlying conditions for further ódestabilisationô untouched. The literature indicates that there is no agreement in a universal definition of stability and that stability needs to be defined for each process/transport/storage/reuse combination.

The evidence indicates that the stability criteria included in Biosolids Guidelines in Australia ï at the National and State level ï can be characterised as follows:

- The stability grading has been replaced in some jurisdictions by a ñpathogenò or ñtreatmentò grading. However, all of them use the same stabilisation processes than the NSW guidelines (anaerobic and aerobic digestion, lime stabilisation, composting and air drying).
- In the National and Western Australia (WA) guidelines the VAR measures are combined with the treatment conditions to create the ñpathogen grading classificationò. Victoria (VIC) and South Australia (SA) use a similar approach as NSW with a separate table for the VAR measures.
- The requirements needed to grade biosolids at a specific level of stability quality are more restrictive in the National, WA and VIC guidelines than in the NSW guidelines, especially for products with a similar classification to class B biosolids. The inclusion of Sludge Retention Time (SRT) requirements in anaerobic digestion and the microbiological verification of performance for approved processes in other states are examples of this. SA guidelines present similar conditions to NSW with some modifications catering for their practices at Bolivar Wastewater Treatment Plant.
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Overseas experiences show that the different approaches taken to the management of stability in biosolids are based on environmental, economic, social and legal constraints found in each country. The policies and practices included in this review show the potential pathways for NSW in relation to encouraging application of high quality biosolids to agricultural land (Norway), the use of a mixed approach via incineration/agricultural usage Germany, Denmark) or the production of ñbio-soilsò (Finland).

The number of programs associated with best practices in the management of biosolids, including those associated with stability, continue to grow and support the existing legislation in countries such as the United Kingdom (UK), Sweden and the United States (US). These programs aim to promote the benefits and reduce the risk of potential óoutrage episodesô associated with poorly stabilised biosolids, which are recognised as the biggest threat to biosolids beneficial reuse programs. Beyond these ôBest Practice Programsõ, a growing number of certification schemes were also found in overseas countries such as the Renare Vatten ï Bättre Kretslopp (ReVAQ)® certification in Sweden and the Biosolids Assurance Scheme (BAS) in the UK.

Restrictions on contaminant concentrations in sludge are tightening, especially in Europe, making almost impossible in some countries to beneficially reuse biosolids on agricultural land unless all the potential contaminants upstream of the wastewater treatment plant are controlled. At the same time there is an increasing level of interest worldwide in recycling phosphorus through the beneficial reuse of biosolids which requires merging pathogen, contaminant and odour dimensions of biosolids processing under a coherent risk management framework.

2.2. Definition

Defining stability in biosolids is a complex issue due to the lack of harmonisation of notions between practitioners, regulators, academics, the waste management industry and the community. For many years, it has been considered that sludge is óstabilisedô when it has been digested, either aerobically or anaerobically (Hartenstein, 1981). However, complaints associated with malodourous events around wastewater treatment plants, transportation and during the application on land of biosolids indicates that this is not the case. Stability in biosolids is associated with putrefaction, and therefore, the ability to resist further putrefaction means biosolids have achieved a óstable stateô. Overall, biosolids need to be stable in order to be properly disposed to land without damaging the environment or creating nuisance conditions (Hartenstein, 1981). These stability definitions can be considered as qualitative or ódescriptiveô and they are still the most common approach to define biosolids stability today.

When we look at the different dimensions associated with stability, the criteria is usually associated with the absence of offensive odours, pathogenic organisms or putrescible material. In earlier approaches, stability was defined depending on the energy available for biological metabolism, on the potential for odours and putrefaction or on detrimental health and environmental aspects (Krishnamoorthy, 1987). As a result, different biological, chemical and physical parameters were used to define stability such as enzyme activity, pH and alkalinity, viscosity among others as shown in Table 1.

Stability is achieved by different stabilisation processes where biodegradable volatile solids are converted into methane or carbon dioxide depending on the treatment pathway chosen at the wastewater solids processing train (anaerobic or aerobic biological processes) (WEF et al., 2012). When thermal conversion is used, these solids are converted into an inert ash (WEF et al., 2012). Stabilisation processes can also be considered as having either a non-reversible or reversible nature. Non reversible stabilisation processes include pressure, heat and oxidation processes (e.g. Cambi), biological stabilisation processes (e.g. composting, anaerobic, aerobic digestion), incineration or formation of glass and thermal reduction processes (e.g. volatile solids are reduced to ash) (WEF et al., 2012). In contrast, in reversible stabilisation processes such as drying and lime addition, a rewetting of the product or a decrease in pH will resume the biological decomposition of the material and the potential for experiencing side effects such as odorous events or the attraction of insects, rodent or birds.

Table 1. Suggested indicators of wastewater solids stabilisation (Switzenbaum, 1997)

Type	Indicators
Physical	Dewaterability and settleability
	Viscosity
	Caloric value and differential thermal analysis
Chemical	Toxicity
	Nitrogen (nitrate)
	Phosphorus (orthophosphate)
	Elemental and ash content
	pH and alkalinity
	Humics and phenolics
	Carbohydrate, protein and lipid content
	Nucleic acids
	VSR
	Chemical Oxygen Demand (COD), Total Organic Carbon (TOC)
Biological	Odour
	Pathogen reduction
	Oxygen uptake rate
	Enzyme activity
	Adenosine Triphosphate (ATP)
	Biochemical Oxygen Demand (BOD)
	Protozoa and rotifers

There is no universal definition to biosolids stability stability or method to measure it. Switzenbaum (1997) concluded in his report to the United States Environmental Protection Agency (USEPA) that *“no one method can assess stability for all cases of biosolids produced for beneficial reuse”.* Some years later, Spinosa and Vesilind (2001) indicated that *"there is no single measure of sludge stability, and the sooner we start to recognise this the better off we will be"*. As a result, a more operational definition to material stability has evolved, in which, each of the stabilisation processes is matched with a recommended stability test as shown in Table 2:

Table 2. Stability protocols (Switzenbaum et al., 2002)

Biosolids product	**Stability test**
Aerobically digested biosolids	Specific Oxygen Uptake Rate (SOUR)
Alkaline stabilised biosolids	pH and change in pH
Aerobically and anaerobically digested biosolids	VSR and Additional Volatile Solids Reduction (AVSR)
Compost	CO_2 evolution

The degree to which stabilisation is accomplished 'lawfully' for biosolids is introduced in the Biosolids Guidelines by using the so called Vector Attraction Reduction (VAR) measures. However, it needs to be understood that biosolids stabilisation is not necessarily guaranteed by fulfilling the VAR requirements included in the guidelines, but it is clear that a fully stabilised product has gone beyond the current VAR requirements to achieve stability. In consequence, there is a close relationship between VAR and the concept of stability (WEF et al., 2012).

Tsang and Jr. (2005) indicated that the current USEPA 40 CFR 503 regulations, which are the basis for the current NSW EPA Biosolids Guidelines, contain a range of conditions which are used to design biosolids facilities that, when met, don't necessarily guarantee that a fully stabilised and low odour product is being produced. Furthermore, the design of the facility according with the guidelines is just the first step in producing a stabilised product and that the operation, training and proper quality control and assurance are equally important to consistently achieve the stabilisation goals of the facility. In short, the facilities should be able to go beyond regulatory demands and meet specific product market needs. This approach has also been advocated by Spinosa and Vesilind (2001) which provides an example on specific criteria and standards for the end use of sludge: *"If sludge is to be used as a fertiliser supplement, then it has to have certain characteristics related to the ultimate use. If the farm is in close proximity to people who would be offended by sludge odours, the odour has to be considered in defining the suitability of the sludge. If the plants grown on the farm are for human consumption, then the level of pathogens in the sludge is important"*.

Some other researchers have described stability as the threshold where organic matter is no longer available for microbial activity, therefore, stability is associated with putrescibility and odour emissions (Braguglia et al., 2014). A volatile-to-total solids ratio below 0.6 in the final product or a VSR higher than 40% in aerobic and anaerobic digestion could be considered as indicators of material stability (Braguglia et al., 2014).

There are also definitions on stability from international standards. For example the British Standard Institution (BSI) Publicly Available Specification (PAS) Standard 110:2014 (BIS, 2014) entitled "*Specification for whole digestate, separated liquor and separate fibre derived from the anaerobic digestion of source segregated biodegradable materials*", which applies for anaerobic digestion (but excludes sewage sludge as an input), defines "*stability*" as "*quality of being stable*" and "*stable*" as "*the point at which the rate of biological activity has slowed to an acceptably low and consistent level and will not significantly increase under favourable altered conditions*". This 'irreversibility' is an expected characteristic to consider a material as stable. It has also been argued before that stability is achieved when sludge constituents have 'humified' and biological degradation is progressing at a very slow rate without offensive odour emissions (Hartenstein, 1981).

As an answer to the lack of harmonisation between different stakeholders involved in the management of biosolids around the world the International Organization for Standardization (ISO) started Working Group 275 in 2013 on sludge recovery, recycling, treatment and disposal covering terminology, characterization methods, digestion, land application, thermal processes, thickening and dewatering and inorganics and nutrients recovery. Outputs from this ISO working group will certainly inform future policies and practices associated with stability in Australia and overseas.

2.3. Issues associated with material stability

Historically, most of the focus on biosolids management has been associated with the enforcement of safe levels of contaminants and pathogens to minimise the risk to public health and the environment, but less focus has been given to the other dimension of 'stability', nuisance odour emissions, which have demonstrated to be critical for public acceptance of beneficial reuse programs of organic residuals around the world.

It is acknowledged that following the VAR measures for each treatment technology, as per the NSW Biosolids Guidelines, reduces the pathogen count significantly but doesn't guarantee a stabilised product (WEF et al., 2012). This has the potential to be problematic, as the various stabilisation technologies could comply with the VAR requirements but may have limitations in achieving an adequate level of stabilisation due to operational or maintenance constraints. For example, biosolids can be produced using anaerobic digesters operated at two different retention times, 10 and 40 days respectively. Both are capable of achieving the VSR requirements under the NSW guidelines (VSR >38%) but the risk of having an odorous product is much higher under the former than in the latter case.

Current NSW guidelines don't have any minimum operational requirements for each stabilisation process - beyond the VAR measures - for the production of lawful Class B products (NSW EPA, 1997), and as a result, there are different sub quality grades within the Class B biosolids category, something that has been recognised by farmers (SMH, 2013). Calls to tighten the VAR measures or provide more detailed conditions for the operation of anaerobic digestion and other stabilisation processes have been recommended in previous biosolids reviews (PSD, 2009).

Using microbiological standards to guarantee the stability quality of all classes of biosolids products has been the approach followed by the regulators. This represents a challenge from an odour perspective, as some stabilisation processes are reversible (e.g. alkali addition, drying) and don't guarantee that biosolids products won't generate offensive odours once the conditions are altered. For example, salmonella and faecal coliforms along with associated odour emissions, have been reported following the drying and stockpiling of anaerobically digested biosolids in Western Australia, in some cases to levels at or above initial pre-stabilisation process treatment with associated odour emissions (Gibbs et al., 1997).

Going beyond the microbiological dimension of stability and incorporating other stabilised sludge quality parameters, such as "low odour" characteristics, into the regulatory framework, is considered crucial for the social acceptance of any beneficial reuse program and has been the driver behind the development of 'Good Practice Manuals' around the world (PURE, 2012, UKWIR, 2015, NBP, 2005). However, the inclusion of an odour category for biosolids is a relatively recent development (Peters et al., 2014b, Marchand et al., 2013). The Canadian province of Quebec was the pioneer in regulating odour emissions in biosolids and it has proven to have helped Quebec in the reduction in the number of odour complaints associated with their biosolids program (Beecher, 2010).

The development of this odour grading approach relies on comparing odour from biosolids to that of farm manures. For example, if biosolids smell better than diary manure, they are given an O1 category and can be beneficially reused without restrictions. If they smell similarly to dairy manure they are given an O2 category and the biosolids are subject to some site restrictions. If the fertiliser residual smells worse than dairy manure but better than hog slurry manure, they are given an O3 category and have more stringent site restrictions. If the smell is worse than hog slurry, they can't be applied on land unless treated to reduce odour nuisance to an acceptable level. While the enforcement of an odour category similarly to the Quebec guidelines seems attractive, the enforcement could present some challenges due to the additional cost to producers in finding alternative routes of disposal when residuals are unable to comply with the regulation (Beecher, 2010).

After more than a decade of beneficial reuse of biosolids on agricultural land in NSW without any evidence of adverse impacts to public health or the environment (NRC, 2002, Pritchard et al., 2010), a proactive engagement with stakeholders around the treatment plants and application sites has taken on a more important position with regard to safeguarding the long term viability of the program. However, the guidelines donôt provide any framework to control risks associated with óoutrage episodesô, particularly odour incidents, that could represent a threat to the continuity of the state-wide beneficial reuse program (Hayes et al., 2014b).

2.4. Policies and practices on material stability

In the following section, ópoliciesô refers to regulations, codes, guidelines and any other legal documents which apply to the beneficial reuse of biosolids in agricultural land and ópracticesô refer to any other non-legally binding documentation relevant to the purposes of this review.

2.4.1. Australia

2.4.1.1. National guidelines

In 2004, the National Resource Management Ministerial Council (NRMMC) as part of the National Water Quality Management Strategy released the Guidelines for Sewerage Systems which comprised five documents including one for the Management of Biosolids (NRMMC, 2004). These were inspired by the USEPA biosolids guidelines and the 40 CFR Part 503 rule (USEPA, 1993) which for stability purposes, are very similar. The national guidelines maintained the risk-based approached from current NSW guidelines, but modified the grading of the stability of biosolids. These changes have been incorporated in some updated guidelines such as those from VIC and WA. There are four different categories of biosolids in the national guidelines, but as 71% of NSW biosolids production in 2015 were classified as Class B and only 6% as class A (PSD, 2015), this review will focus on class B only. The most relevant considerations from the National Guidelines to the stability requirements included in the NSW Biosolids Guidelines for class B biosolids are associated with the ñOther Conditionsò and they are presented, and compared, in Table 3

Previous guidelines reviews within the Australian context have considered the vector attraction requirements used for some of the treatment processes as ñ*inadequate in some aspects to reduce the odour potential of biosolids*ò (PSD, 2009) and have advocated for tighter VAR measures for biosolids. It can be seen from Table 3 that the National Guidelines are more restrictive than the NSW Biosolids Guidelines in relation to the operational

Table 3. Comparison on stability requirements between Pathogen Grade P3 in the National Guidelines and Stabilisation Grade B in NSW

(NSW EPA, 1997, NRMMC, 2004)

Process	National Guidelines			NSW Guidelines		
	Approved Process?	Microbiological criteria?	Other conditions	Pathogen Reduction Process?	Microbiological criteria?	Vector attraction reduction requirements
Anaerobic digestion	Yes	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight)	15 days at 35 °C. or 60 days at 15 °C > 38% volatile solids reduction	Yes	No	1. Mass of volatile solids in the biosolids shall be reduced by a minimum of 38% 2. Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °C
Aerobic digestion	Yes	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight)	40 days at 20 °C or 60 days at 15 °C > 38% volatile solids reduction	Yes	No	1. Aerobically digested biosolids, which do not meet requirement 1 above, must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes). 2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.
Air Drying	Not included under grade P3 but under P2 and P1. P2 requires biosolids to be heated to > 70 °C and dried to solids content of at least 75% by weight, < 10 *Salmonella* per 50 gram of final product, < 1000 *E. Coli* (or thermotolerant coliforms) per gram of final product.			Yes	No	1. For biosolids, which contain stabilised solids only, the proportion of dry solids shall be at least 75%. 2. For biosolids, which contain unstabilised solids generated in a primary wastewater treatment, process the proportion of dry solids shall be at least 90%.
Composting	Yes	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight)	Aerobic conditions to be maintained 5 days at > 40 °C including 4 hours at > 55 °C.	Yes	No	Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45°C.
Lime stabilisation	Not included under grade P3 but under P1 as ŗpH and heatingò which include a condition for air-drying the product to a final solids content > 50% by weight after a pH > 12 and a temperature > 52 °C.			Yes	No	The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.
Extended aeration	Included under Aerobic Digestion			Yes	No	At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.
Other processes	Criteria as determined by State/territory regulatory authority			Criteria as determined by NSW EPA		

conditions of anaerobic digestion and composting. Lime stabilisation and air drying have been removed from the P3 category and have been included under P1 and P2 categories with additional restrictions. Extended aeration is included under aerobic digestion, which by itself has similar operating conditions in both guidelines. Long term storage is included under P2 subject to the following microbiological criteria: <10 *Salmonella* per 50 grams of final product and <1000 *E. coli* (or thermotolerant coliforms) per gram of final product.

The incorporation of minimum operational conditions, such as a minimum SRT for anaerobic digestion, enables the regulator to ensure all biosolids have a minimum treatment before being applied to land, even when maintenance or other constraints at the plant could reduce the effectiveness of the treatment for pathogen reduction purposes. The inclusion of microbiological criteria also provides a performance-based target which can be used to assess if the process is achieving a reasonable pathogen reduction performance, thus shouldn't be considered as an indication of effective stabilisation.

The following sections compare and contrast the policies and practices of other relevant national jurisdictions. Queensland is not included because this jurisdiction uses the NSW guidelines as a guidance document for the management of biosolids in the State.

2.4.1.2. South Australia (SA)

The current guidelines in SA were officially updated last in 1997; however, a draft was presented for consultation in 2009 and this effectively serves as the current state guideline (SAEPA, 2009). The draft SA guidelines include many of the new features found at the National and state level documents. Table 4 includes the draft SA guidelines side-by-side, with the current NSW guidelines. Nearly 100% of the biosolids in SA are applied to agricultural land as a class A stabilised product (Short, 2016).

2.4.1.3. Western Australia (WA)

Western Australia updated their biosolids guidelines in 2012 (DECWA, 2012). Stability was removed as a criterion for grading and was incorporated into a general pathogen grading classification. Pathogen grade is defined as: *“based on the level of treatment undertaken to achieve desired microbial limits and a reduction in odour and vector attraction for biosolids and biosolids products”*. The pathogen grade classification has a similar structure to the National Guidelines described in previous sections and uses four levels for pathogen grade P1, P2, P3 and P4.

The most relevant feature of the WA updated guidelines in contrast to the current NSW Biosolids Guidelines in relation to stability is the use of a performance approach to the different approved treatment methods. This includes additional process conditions and microbiological verification. For example, if raw sludge is treated using anaerobic digestion

Table 4. Comparison on stability requirements between Stabilisation Class B in SA (draft guidelines) and Stabilisation Grade B in NSW (NSW EPA, 1997, SAEPA, 2009)

Process	SA draft guidelines			NSW Guidelines		
	Approved Process?	Microbiological criteria?	Other conditions	Pathogen Reduction Process?	Microbiological criteria?	Vector attraction reduction requirements
Anaerobic digestion	Yes, if > 20 deg.C for > 60 days or > 35 to 55 deg.C for > 15 days	Yes, < 1,000 E. coli per gm total solids (dry weight)	Vector attraction reduction controls (VSR > 38%)	Yes	No	1. Mass of volatile solids in the biosolids shall be reduced by a minimum of 38% 2. Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °Celsius
Aerobic digestion	Yes, if >20 deg.C for >40 days or >15 deg.C for > 60 days		Vector attraction reduction controls (VSR > 38%)	Yes	No	1. Aerobically digested biosolids, which do not meet requirement 1, above must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes). 2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.
Air Drying	Yes if, centrifuged cake mixed with an equal volume of previously dried biosolids and turned to mix and dry aged not less than 60 days and not less than 50% solids.		Biosolids containing no unstabilised solids dried to Ó75% solids content Biosolids containing unstabilised solids dried to Ó90% solids content	Yes	No	1. For biosolids, which contain stabilised solids only, the proportion of dry solids shall be at least 75%. 2. For biosolids, which contain unstabilised solids generated in a primary wastewater treatment, process the proportion of dry solids shall be at least 90%.
Composting	Yes, if aerobic composting at >40 deg.C for > 5 days, including at least 4 hours at >55 °C using windrows, aerated static pile or in vessel methods		Aerobic treatment for Ó14 days at temperatures: minimum 40 °C and average > 45 °C	Yes	No	Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C.
Lime stabilisation	Yes, if pH is maintained at > 12 for > 2 hours		Alkaline treatment pH raised to Ó12, and without addition of further alkali pH maintained at Ó12 for 2 hrs and then at pH Ó11.5 for an additional 22 hours	Yes	No	The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.
Medium term storage	Sludge is anaerobically digested, dried by lagoon evaporation and then stored for at least one year to achieve a minimum solids content >75% by weight. Undigested sludge dried lagoon evaporation and then stored for at least three years to achieve a minimum solids content >75% by weight.		Not included	Not included		
Extended aeration	Included under Aerobic Digestion			Yes	No	At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.
Other processes	Criteria as determined by SAEPA			Criteria as determined by NSW EPA		

and the VSR is higher than 38%, the digested sludge is classified as class B biosolids under NSW guidelines. However, under the WA guidelines, the raw sludge needs to be treated using mesophilic anaerobic digestion process at 35 ± 3°C for at least 15 days with a minimum of 1.5 $\log_{10}$ reduction in the pathogen count. The VSR needs to be higher than 38% at the digester (as in the NSW guidelines) and have an *E. coli* count lower than 2,000,000 per gram of dry final biosolids. This enable the regulator to *validate* the true effectiveness of the stabilisation processes when operational issues such as grit accumulation, maintenance and cleaning compromise their adequate performance.

The WA guidelines also include the following statement for all the pathogen grades under the other conditions category: *"Final biosolids do not generate offensive odours when couple with management controls"*. This refers to other section of the guidelines where is indicated that *"The calculation of pathogen log removals, following treatment with a quality assurance/quality control program, is considered a better approach for microbial risk management rather than only end-point quality monitoring for microbial indicators"*. This is good for managing the risk at the source regardless of the technology used, but also introduces challenges in monitoring microbial indicators at the plant level due to the time lag associated with the analytical procedures needed to measure them. While it can be useful for reporting the treatment performance on a monthly basis (as requested by the WA guidelines), it is harder to use it as an effective process control tool at the plant level to ensure stability due to the smaller time scales (e.g. hours or less) needed for corrective actions. A comparison between WA and NSW guidelines is presented in Table 5.

2.4.1.4. Victoria (VIC)

Victoria updated its biosolids guidelines in 2004 (Victoria EPA, 2004). Victorian guidelines are 'aligned' to the proposed National Guidelines, but use a treatment grade instead of a pathogen grade. The potential risks associated with unstabilised material are recognised in the spirit of the guidelines and addressed somewhat by mentioning that **"*the risk to air of odours from inadequately stabilised biosolids also needs to be assessed*"**. VAR measures are acknowledged to relate to odour emissions and they are included under the "*other suggested controls*" for each treatment grade.

It is also recognised that VAR measures were not developed to control offensive odours and that at times ***additional stabilisation is required***. The VIC guidelines also include biosolids quality guidance for the intended use, so the classification includes the contaminant and treatment grading. Similar to the NSW guidelines, the VAR measures are included as a separate category. Table 6 and Table 7 present a comparison between the VIC and NSW guidelines.

Table 5. Comparison on stability requirements between Pathogen Grade P3 in WA and Stabilisation Grade B in NSW

(DECWA, 2012, NSW EPA, 1997)

Process	WA Guidelines			NSW Guidelines		
	Approved treatment method?	Maximum pathogen levels?	Other conditions	Pathogen Reduction Process?	Microbiological criteria?	Vector attraction reduction requirements
Anaerobic digestion	Yes, if >15 °C. for > 60 days	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight) Strongyloides & Hookworm (viable Ova) <1 per 50 grams of dry final biosolids (only required north of the 26th parallel)	Final biosolids do not generate offensive odours when coupled with management controls, and with a volatile solids reduction of >38%	Yes	No	1. Mass of volatile solids in the biosolids shall be reduced by a minimum of 38% 2. Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °Celsius
	Yes, if >35 ± 3°C. for > 15 days	Yes, Minimum pathogen reduction of 1.5 log reduction through digestion (pathogen count reduced by 1.5 orders of magnitude from start to finish of sludge treatment process)	Trigger value *E. coli* ï less than 2,000,000 counts per gram of dry final biosolids, with a volatile solids reduction of >38%			
Aerobic digestion	Yes, if >20 °C. for >40 days >15 °C. for > 60 days	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight) Strongyloides & Hookworm (viable Ova) <1 per 50 grams of dry final biosolids (only required north of the 26th parallel)	Final biosolids do not generate offensive odours when coupled with management controls, and with a volatile solids reduction of >38%	Yes	No	1. Aerobically digested biosolids, which do not meet requirement 1, above must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes). 2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.
Air Drying	Not included under grade P3 but under P2 and P1. P2 requires biosolids to be heated to > 70 °C for 1 hour and dried to solids content of at least 90% by weight or 75% if sludge has been digested < 1,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight). Strongyloides & Hookworm (viable Ova) <1 per 50 grams of dry final biosolids (only required north of the 26th parallel) Final biosolids do not generate offensive odours when coupled with management controls. Final product to be kept dry until applied			Yes	No	1. For biosolids, which contain stabilised solids only, the proportion of dry solids shall be at least 75%. 2. For biosolids, which contain unstabilised solids generated in a primary wastewater treatment, process the proportion of dry solids shall be at least 90%.
Composting	Yes, if aerobic composting at >40 deg.C for > 5 days, including at least 4 hours at >55 °C Process control as per AS 4454-2003	Yes, < 2,000,000 *E. coli* (or thermotolerant coliforms) per gram (dry weight) Strongyloides & Hookworm (viable Ova) <1 per 50 grams of dry final biosolids (only required north of the 26th parallel)	Final biosolids do not generate offensive odours when coupled with management controls, and with a volatile solids reduction of >38%. Weed seed controls may be needed in agricultural or landscape applications	Yes	No	Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C.
Lime stabilisation	Yes, if pH is maintained at > 12 for > 3 hours	As above	Lime amended biosolid (LAB) product is applied within 7 days	Yes	No	The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.
Extended aeration	Included under Aerobic Digestion			Yes	No	At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.
Other processes	Table 3 of the WA guidelines			Criteria as determined by NSW EPA		

Table 6. Comparison on stability requirements between Treatment Grade T3 in Victoria and Stabilisation Grade B in NSW

(Victoria EPA, 2004, NSW EPA, 1997)

<table>
<tr><th rowspan="2">Process</th><th colspan="3">Victorian Guidelines</th><th colspan="3">NSW Guidelines</th></tr>
<tr><th>Suggested treatment process?</th><th>Microbiological criteria?</th><th>Other suggested controls</th><th>Pathogen Reduction Process?</th><th>Microbiological criteria?</th><th>Vector attraction reduction requirements</th></tr>
<tr><td>Anaerobic digestion</td><td>Yes, if
>15 deg.C
for > 60 days
>35 deg.C
for > 15 days</td><td rowspan="2">Yes,
< 2,000,000 E. coli
Most Probable Number (MPN)/ g (dw)</td><td>Vector attraction reduction controls (VSR > 38%) and product that, coupled with management controls does not generate offensive odours.

Weed seed controls may be needed in agricultural or landscape applications</td><td>Yes</td><td>No</td><td>Mass of volatile solids in the biosolids shall be reduced by a minimum of 38%
Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °Celsius</td></tr>
<tr><td>Aerobic digestion</td><td>Yes, if
>20 deg.C for >40 days
>15 deg.C for > 60 days</td><td>Relevant vector attraction reduction controls (VSR > 38%) and product that, coupled with management controls does not generate offensive odours.

Weed seed controls may be needed in agricultural or landscape applications</td><td>Yes</td><td>No</td><td>1. Aerobically digested biosolids, which do not meet requirement 1, above must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes).
2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.</td></tr>
<tr><td>Air Drying</td><td colspan="3">Not included under grade T3 but under T2 and T1.</td><td>Yes</td><td>No</td><td>For biosolids, which contain stabilised solids only, the proportion of dry solids shall be at least 75%.
For biosolids, which contain unstabilised solids generated in a primary wastewater treatment, process the proportion of dry solids shall be at least 90%.</td></tr>
<tr><td>Compostin g</td><td>Yes, if
aerobic conditions maintained > 5 days, at >40 °C including 4 hours at >55 °C</td><td>Yes,
< 2,000,000 E. coli
MPN/ g (dw)</td><td>Final biosolids do not generate offensive odours when coupled with management controls, and with a volatile solids reduction of >38%.

Weed seed controls may be needed in agricultural or landscape applications</td><td>Yes</td><td>No</td><td>Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C.</td></tr>
<tr><td>Lime stabilisatio n</td><td colspan="3">Not included under grade T3 but under T1 only.</td><td>Yes</td><td>No</td><td>The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.</td></tr>
<tr><td>Extended aeration</td><td colspan="3">Not included</td><td>Yes</td><td>No</td><td>At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.</td></tr>
<tr><td>Other processes</td><td colspan="3">Based on E. coli criteria and 1 log reductions in Salmonella and enteric viruses. Vector attraction reduction controls also required</td><td colspan="3">Criteria as determined by NSW EPA</td></tr>
</table>

Table 7. Comparison on stability requirements between Treatment Grade T2 in Victoria and Stabilisation Grade B in NSW

(Victoria EPA, 2004, NSW EPA, 1997)

<table>
<tr><th rowspan="2">Process</th><th colspan="3">Victorian Guidelines</th><th colspan="3">NSW Guidelines</th></tr>
<tr><th>Suggested treatment process?</th><th>Microbiological criteria?</th><th>Other suggested controls</th><th>Pathogen Reduction Process?</th><th>Microbiological criteria?</th><th>Vector attraction reduction requirements</th></tr>
<tr><td>Anaerobic digestion</td><td colspan="3">Not included</td><td>Yes</td><td>No</td><td>Mass of volatile solids in the biosolids shall be reduced by a minimum of 38%
Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °Celsius</td></tr>
<tr><td>Aerobic digestion</td><td>Yes, if
Aerobic conditions at 55-60°C for Ó10 continuous days. Final product dried to Ó50% solids</td><td rowspan="3">Yes,
< 10 Salmonella/ 50 g dw,
< 1,000 E. coli MPN/ g (dw)</td><td>Relevant vector attraction reduction controls (VSR > 38%) and product that, coupled with management controls does not generate offensive odours.</td><td>Yes</td><td>No</td><td>1. Aerobically digested biosolids, which do not meet requirement 1, above must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes).
2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.</td></tr>
<tr><td>Air Drying</td><td>Yes, if
biosolids are heated to Ó70°C and dried to a solids content of at least 75% w/w.</td><td>Relevant vector attraction reduction controls (solids must be digested) and product that, coupled with management controls does not generate offensive odours.</td><td>Yes</td><td>No</td><td>For biosolids, which contain stabilised solids only, the proportion of dry solids shall be at least 75%.
For biosolids, which contain unstabilised solids generated in a primary wastewater treatment, process the proportion of dry solids shall be at least 90%.</td></tr>
<tr><td>Composting</td><td>Yes, if
The temperature of all compost material to be Ó53°C for Ó5 continuous days or Ó55°C for Ó3 continuous days. (NB. Although this criteria is comparable to T1, it is also included as a T2 process in reflection that achieving the stringent T1 E.coli limits may require specialised techniques.</td><td>Final biosolids do not generate offensive odours when coupled with management controls, and with a volatile solids reduction of >38%.

Weed seed controls may be needed in agricultural or landscape applications</td><td>Yes</td><td>No</td><td>Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C.</td></tr>
<tr><td>Lime stabilisation</td><td colspan="3">Not included under grade T2 but under T1 only.</td><td>Yes</td><td>No</td><td>The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.</td></tr>
<tr><td>Extended aeration</td><td colspan="3">Not included</td><td>Yes</td><td>No</td><td>At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.</td></tr>
<tr><td>Other processes</td><td colspan="3">Based on achieving Salmonella and E.coli criteria and demonstration of 2 log Taenia saginata and enteric virus removal or batch testing to demonstrate < 1 Taenia ova per 10g and < 2 enteric virus PFU per 10g. Vector attraction reduction controls also required.</td><td colspan="3">Criteria as determined by NSW EPA</td></tr>
</table>

2.4.2. Overseas

2.4.2.1. United Kingdom (UK)

In the UK, the use of biosolids in agriculture is regulated by the Sludge (use in Agriculture) Regulations (SI, 1989), the Code of Good Agricultural Practice (DEFRA, 1993) and the Environmental Protection Act for Sewage Sludge incineration and landfilling (UK Government, 1990). The regulations refer to treated sludge as ñ*sludge or septic tank sludge which has undergone biological, chemical or heat treatment, long-term storage or any other appropriate process so as to significantly to reduce its fermentability and the health hazards resulting from its use".* Fermentability in this context could be associated with instability as this refers to the putrefaction of the sludge when left untreated.

The code aims to cover stability under the item ñcò of the objectives: ñ*public nuisance and water pollution are avoided*ò as public nuisance is commonly referred as odour emissions from biosolids production, transport or application. *"Public nuisance from smell"* needs to be minimised and should be taken into account. The code presents ñ*examples of effective sludge treatment processes*ò such as sludge pasteurisation, mesophilic anaerobic digestion, thermophilic anaerobic digestion, composting and lime stabilisation. It is acknowledged that the most effective odour control is the adequate treatment of the sludge but that ñ*some treated sludges can still be offensive*ò.

Since 1999, the British Retail Consortium (BRC) and Water UK agreed to implement a voluntary agreement on standards of practice called ñthe Safe Sludge Matrixò (ADAS, 1999) which consist of the minimum acceptable levels of treatment for any type of sewage sludge and the potential for application to different crop types. The minimum acceptable levels of treatment are described in the document and classified as conventionally and enhanced treated sludges. The former refers to treatment processes and standards able to destroy 99% of pathogens in the sludge and the latter to treatment processes ensuring sludge that is *Salmonella*-free and where 99.9999% of pathogens have been eliminated (equivalent to 6 $\log_{10}$ reduction).

From the material stability point of view, both policies lack details on odour considerations, but indirectly acknowledge that these treatments are able to reduce odours; however, thresholds and standards for this are not included. There are no VAR rules within the UK context related to the stabilisation technologies as in the NSW guidelines. In contrast, the UK code of practice specifies some operational parameters for each treatment technology as shown in Table 8.

Table 8. Comparison of UK stabilisation requirements between UK and NSW

(DEFRA, 1993, NSW EPA, 1997)

Treatment Process	UK requirements		NSW requirements
Anaerobic digestion	Mesophilic	Mean retention period of at least 12 days primary digestion in temperature range 35°C±3°C or of at least 20 days primary digestion in temperature 25°C±3°C followed in each case by a secondary stage which provides a mean retention period of at least 14 days.	1. Mass of volatile solids in the biosolids shall be reduced by a minimum of 38%. 2. Anaerobically digested biosolids which do not meet the previous requirement must have no more that 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37 °Celsius
	Thermophilic	Mean retention period of at least 7 days digestion. All sludge to be subject to a minimum of 55°C for a period of at least 4 hours.	
Aerobic digestion	Not included in the UK code of practice		1. Aerobically digested biosolids which do not meet requirement 1 above (mass of volatile solids in the biosolids shall be reduced by a minimum of 38%) must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes). 2. Specific oxygen uptake rate for biosolids treated by an aerobic process shall be less than 1.5 mg 02/hour/g total solids at 20°C.
Air Drying	Not included in the UK code of practice		1. For biosolids which contain stabilised solids only, the proportion of dry solids shall be at least 75%. 2. For biosolids which contain unstabilised solids generated in a primary wastewater treatment process the proportion of dry solids shall be at least 90%.
Composting	The compost must be maintained at 40°C for at least 5 days and for 4 hours during this period at a minimum of 55°C within the body of the pile followed by a period of maturation adequate to ensure that the compost reaction process is substantially complete.		Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C.
Lime stabilisation	Addition of lime to raise pH to greater than 12 and sufficient to ensure that the pH is not less than 12 for a minimum period of 2 hours. The sludge can then be used directly.		The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.
Extended aeration	Conditioning of untreated sludge with lime or other coagulants followed by dewatering and storage of the cake for a minimum period of 3 months. If sludge has been subject to primary mesophilic anaerobic digestion, storage to be for a minimum period of 14 days.		At least 20 days continuous or intermittent extended aeration including aerobic digestion time followed by six (6) months storage of biosolids in a lagoon or equivalent process.

UK policies and practices share similar treatment technologies in a slightly different classification to the grade A and B of the NSW Biosolids Guidelines. In the UK, the definition of stability of biosolids is not explicitly identified, but considers different effective treatment method and classifies them as conventional and/or enhanced treatment. The application of biosolids on land is recognised as the most environmentally-friendly practice in most circumstances due to their contribution of nutrients and stable organic matter to soils (UKWIR, 2015).

The UK also has a Good Practice Guidance Leaflet (UKWIR, 2015) where the different stabilisation processes and their performance conditions are outlined. For example, for anaerobic digestion, temperature (å35°C) and SRT (15-20 days) are specified. It is stated that the liquid digestate is dewatered ñ*to produce a stabilised digested biosolids cake*ò. It also indicates the use of other advanced digestion technologies and pre-treatment technologies to improve the process. For lime stabilisation, the option of mixing raw or digested sludge is presented, indicating that the increase in temperature and pH remove ñ*potentially dangerous microorganisms*ò. For thermal drying, temperatures above 100 °C are expected to remove water and pathogens and stabilise the material. For composting, stabilisation is also mentioned where the rise in temperature during the aerobic thermophilic phase stabilises organic matter and kills potentially harmful microorganisms.

One interesting aspect of the good practice guide is the inclusion of a HACCP plan per site, which ensures the treatments and control processes are effective in reducing potentially harmful microorganisms. The introduction of the Biosolids Assurance Scheme (BAS) is expected to provide an integrated and auditable standard to demonstrate best practices, legislation compliance and good outcomes for the environment in the management of biosolids (OFWAT, 2016).

2.4.2.2. Norway

Norway has one of the most stringent regulations in the world associated with the application of biosolids on agricultural land. The current legislation enacted in 2003 named ñRegulation of organic fertilisersò covers all organic materials applied on land such as food processing waste, farm waste and sewage sludge among others (Paulsrud and Nybruket, 2007). The enforcement agency is the Norwegian Food Safety Authority (NFSA) and the following requirements are included in the regulations:

- Biosolids needs to be produced using a quality assurance system;
- General requirements are given for material stability ï linking it to odour emissions ï but no parameters or figures are provided;

- Other requirements for biosolids include labelling, product registration, storage of products before use and special crop restrictions;
- All organic fertilisers need to achieve the following targets for hygienisation:
    - No *Salmonella* sp. in 50 grams of sludge
    - No viable helminth ova
    - Less than 2,500 faecal coliforms per gram dry solids.

Due to ñproblems with odour complaintsò, some producers upgraded their plants before the legislation was enacted. The following process configurations were implemented to comply with the new regulations for stabilisation and hygienisation (Paulsrud and Nybruket, 2007):

- Thermophilic aerobic digestion
- Thermophilic aerobic pre-treatment + mesophilic anaerobic digestion
- Pre-pasteurisation + mesophilic anaerobic digestion
- Thermal hydrolysis + mesophilic anaerobic digestion
- Mesophilic anaerobic digestion + thermal drying
- Thermophilic anaerobic digestion
- Composting (windrow or in-vessel)
- Lime treatment
- Long-term, minimum of 3 years, storage of dewatered sludge

Different studies have collected and summarised the operational experiences and unit costs associated with these stabilisation and disinfection routes showing that pre-treatments (thermophilic aerobic, pasteurisation and thermal hydrolysis) in combination with mesophilic anaerobic digestion provided the cheapest, most reliable and effective way to achieve the stabilisation criteria set by the authorities (Ødegaard et al., 2002).

The regulators in Norway did not consider a separate stability classification (e.g. class A versus B) should exist for the hygienisation and stabilisation criteria of organic derived fertilisers. This approach is considered as ñprecautionaryò (LeBlanc et al., 2008) or ñno risk based backgroundò (Paulsrud and Nybruket, 2007), but the main rationale for the authorities behind creating a unified high quality classification for biosolids was the likelihood that farmers or other stakeholders will refuse receiving ñclass Bò biosolids even if they are incorporated into the soil in less than 24 hours. It is also reported that plant owners considered the investment needed to achieve a better quality product as marginal, because they needed to install stabilisation processes to comply with the regulations anyway. Main end uses of biosolids in Norway are agricultural lands and ñgreen areasò such as parks, reclamation sites, road sides and any other areas were crops are not harvested for consumption. The role of biosolids in achieving phosphorus recycling targets is also expected to maintain the relevance of the beneficial reuse on land for many years to come (Hanserud et al., 2016).

2.4.2.3. European Union (EU)

The management of sludge in the European Union is subject to the following directives (PURE, 2012):

- The Sewage Sludge Directive. Council Directive of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC)
- The Urban Waste Water Treatment Directive. Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC)
- The Nitrates Directive. Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC)
- The Landfill Directive. Council Directive of 26 April 1999 on the landfill of waste (1999/31/EC)
- The Incineration Directive. Directive of the European Parliament and of the Council of 4 December of 2000 on the incineration of waste (2000/76/EC)
- The Renewable Energy Directive. Directive of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable sources in the internal electricity market (2001/77/EC)
- The Fertilisers Regulation. Regulation of the European Parliament and of the Council of 13 October 2003 relating to fertilisers (Nr 2003/2003)
- The Waste Framework Directive. Directive of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (2008/98/EC)
- The Priority Substances Directive. Directive of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy.

Sewage sludge for agricultural application in the EU needs to be transformed into ñtreated sludgeò after undergoing chemical, biological or heat treatment, long-term storage or any other treatment to significantly reduce its fermentability and the health hazards associated with its use. Since the promulgation of the sludge directive in 1986 (Mininni et al., 2015), many countries have enforced new requirements mainly focused on heavy metals and organic contaminants (Gendebien, 2010, Christodoulou and Stamatelatou, 2016). The application of the directive depends on the local conditions and specific context of each of the member states, so there is a wide range of policies and practices in place within the EU as shown in Table 9. Most countries have prohibited the use of untreated sludge and effectively most of them use anaerobic or aerobic digestion, lime conditioning, thermal drying, composting or long term storage for stability purposes.

The EU sewage sludge directive is not prescriptive in relation to the ápproved processesôto produce treated sludge. The technologies that can be used to reduce the ñfermentabilityò (which effectively means stabilising the sludge), are covered by national legislation and a comparison is shown in Table 9. Some countries within the EU follow the sewage sludge directive which is less stringent than current regulations in NSW. We have included details of national legislation from different EU countries in the following subsections (ANDERSEN, 2001).

The other directives mentioned above have had both positive and negative impacts in the way stabilisation is evaluated in Europe For example, the renewable energy directive positively impact the stabilisation of sludge using anaerobic digestion and the incineration directive has tightened the rules for emissions associated with the incineration of the sludge. New targets for phosphorus recycling may impact the way some utilities process the sludge in order to comply with the regulations (Evans, 2012).

Finland

In Finland biosolids are beneficially reused mostly through the production of composts or ñBio-Soilsò which account for more than 90% of the final disposal of the dewatered cake. Very little direct application on agricultural land is practiced. The use of sewage sludge in agricultural land is regulated by the Government Decision # 282 of 14/04/94 and any fertiliser of organic origin is regulated by the Fertiliser Act # 539 of 29/06/2006. The following are considered as acceptable treatment methods for the stabilisation of sludge (PURE, 2012):

- Digestion ï sludge is treated under anaerobic conditions at a minimum temperature of 33-35 °C for several weeks.
- Addition of lime ï even mixing of lime into the sludge matrix to achieve an initial pH > 12
- Other method capable of significantly reduce pathogens, odours and harm to health or environment.

After the sludge has been stabilised and dewatered, it is composted with bark and peat. The compost is then mixed with crushed biotite stones, limestone and sand to produce Bio-Soil (Metsapirtin) which is used for landscaping, gardening and other green applications. The reason behind the high levels or composting in Finland are associated with the very low levels of heavy metals imposed for the direct application of biosolids on agricultural land

(Evans, 2012). The regulations in Finland provides an example of a high recycling rate of biosolids, mainly via gardening and landscaping routes, without relying on incineration or landfilling.

Similarly to Finland, biosolids have been used as a raw material for the production of compost in New South Wales. Biosolids produced in plants around the Sydney Metropolitan region use the composting route when direct application of biosolids is not feasible, mainly due to quality problems with Class B biosolids such as offensive odours, stickiness or poor transportability. This presents a different approach to Finland, where composting has been implemented as a way to recover valuable materials and not as an alternative route when quality expectations are not met.

Denmark

There are some similarities between Denmark and NSW. The stabilised category has restrictions on the type of crops that could be grown and the time limits for the incorporation on biosolids into the soil and it is effectively a Class B category from a NSW perspective. The controlled pasteurisation category will be similar to a Class A category in NSW with similar microbiological restrictions. The controlled composting route is similar to the requirements for composting biosolids in the NSW guidelines but at a higher temperature. No details are given for VAR methods or performance requirements. Additional details are provided in Table 9

Germany

The legislation governing sludge management in Germany includes the Closed Substance and Waste Management (amended in 2012), the Sewage Sludge Ordinance (1992, in amendment), the Fertiliser Ordinance (2012, last modification in 2015) and others such as the Federal Emissions Control Act (1990), the Waste Act (1994) and Technical Instructions on Wastes for Sewage Sludge thermal disposal (1993) (Wiechmann et al., 2013, Klages, 2016). It is the view of the review team that the legislation governing sludge management in Germany is changing and incorporating different perspectives associated with the management of phosphorus flows and renewable energy. While application to agricultural land will continue for small plants, for larger plants the practice is expected to cease by 2025. A move towards incineration technologies with phosphorus recovery is clear.

Table 9. National policy requirements in relation to sewage sludge stabilisation in selected European countries and current practices□

((Christodoulou and Stamatelatou, 2016, Kelessidis and Stasinakis, 2012, LeBlanc et al., 2008, ANDERSEN, 2001, Wiechmann et al., 2013, PURE, 2012, Malmqvist et al., 2006))

Country	Stabilisation requirements for agricultural use	Stabilisation technologies in use			
		Aerobic	Anaerobic	Lime	Composting
Finland	National legislation considers biosolids as fertilising products (Government Decree 539/2006). Sludge aimed for land application should be stabilised using digestion, addition of lime or any other method capable of significantly reducing its pathogen content, odours and harm to health or the environment arising from the sludge application. Treatments include mesophilic and thermophilic digestion, composting, thermal drying and lime stabilisation. Most common process is composting and mesophilic anaerobic digestion. 73% of the water utilities compost their sludges. Mesophilic and thermophilic digestion processes are used.	Common use	Most common use	Rarely used	Most common use
Denmark	National regulation provides 4 levels of treatment: untreated, stabilised, controlled composting and controlled pasteurisation. Stabilisation processes are defined as anaerobic or aerobic digestion, aeration, composting without temperature control, 6 months of storage or addition of lime. Controlled composting means checking temperature daily for no less than 2 weeks over 55ŠC. Controlled pasteurisation means addition of lime to achieve a pH of 12 for three months, thermophilic digestion with an option of mesophilic digestion afterwards and pasteurisation for not less than 1 hour. Mesophilic and thermophilic digestion processes are used.	Common use	Common use	Common use	Common use
Germany	National legislation is issued at the Federal level but each relevant authority in the ñLanderò is responsible for the enforcement and potential additional regulations if required. Eleven out of fourteen states favour the use of sludge in agriculture. While details on the stabilisation methods are not included in the legislation, there is a prohibition of using untreated sludge for agricultural applications and only sludge with 5% of organic matter is accepted on landfills since 2005. Incineration has grown significantly (28% between 2000 and 2009). Most popular methods for stabilisation are anaerobic digestion and addition of lime and composting to a lower extent. Temperature phase anaerobic digestion (TPAD) is also used.	Small plants	Common use	Common use	Rarely used
Sweden	Regulation includes the following techniques for stabilisation: biological, chemical or heat treatment, long-term storage or any other process to significantly reduce the health hazards resulting from its use. There is a voluntary agreement called REVAQ between the Federation Swedish Farmers (LRF), the Swedish Water and Waste Water Association (VAV), the Swedish Food Federation, the Swedish Food Retailers Federation in cooperation with the Swedish Environmental Protection Agency to certify the quality of biosolids by improving the quality of the influent, providing transparency on how biosolids are produced and ensuring biosolids are produced in a responsible way and fulfilling the legal requirements	Common use	Common use	Common use	Common use

* Key laws impacting the management of biosolids in the European Union (EU27) include the Sewage Sludge Directive (1986), Urban Waste Water Treatment Directive (UWWTD, 91/271/EEC), Landfill of Waste (Directive 99/31/EC), Waste Incineration Directive (Directive/2000/76/EC)

From a stabilisation perspective, anaerobic digestion will continue to be the most common technology for large plants and aerobic stabilisation for small plants. Further treatment for P recovery will need to consider if the sludge is going to be incinerated or not. Regardless of the future disposal routes or standards, the stabilisation of sewage sludge in Germany, especially the biological process alternatives, will have a predominant role (DWA, 2003).

The way stabilisation is managed in Germany provides important lessons for future updates of the NSW Biosolids Guidelines:

1. The legislation does not provide a detailed definition of stability but rather what stabilisation and pseudo-stabilisation means:
    - Stabilisation: Process of sludge treatment for extensive reduction of odour-forming content substances and organic solids in the sludge. Desired secondary objectives are the improvement of the dewatering capability and the reduction of pathogenic agents.
    - Pseudo-stabilisation: Process of sludge treatment where the treated product is not biologically degradable as long as certain conditions (e.g. pH value or dryness) are maintained. If these conditions are no longer maintain the biological degradation restarts.
2. It is the role of the Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. (DWA) to develop standards clarifying any ógapô in the legislation associated with the definition of terms and the required degrees of stabilisation depending on the utilisation or disposal objective. means for each utilisation or disposal objective. For example, the DWA standard M-368E (DWA, 2003) (the most recent is from 2014 but is published in German only) provides a table with these two dimensions and it is reproduced in Figure 1 to inform future developments.
3. There is a clear separation between the objectives of stabilisation and hygienisation processes. Stabilisation doesnôt mean pathogen-free. Hygienisation is needed for unrestricted use. Stabilisation is needed even if pathogens are reduced to the point were counting is not possible.
4. The DWA standard clearly states the main objective of stabilisation is ñ*the stabilisation of the substrate*ò and lists as secondary objectives the following (DWA, 2003):
    - The reduction of sludge/solid matter quantities
    - The improvement of the dewatering ability of the sludge
    - The reduction of pathogens
    - The production of biogas (anaerobic stabilisation only)
    - The creation of buffer and storage space for sludge treatment

Table 1: Required degrees of stabilisation assigned to utilisation or disposal objectives

Utilisation or disposal objective	Required degree of stabilisation
Utilisation in farming/agriculture in liquid form	Completely stabilised**
Utilisation in farming/agriculture as well as in land-scaping and in recultivation in dewatered form	Completely stabilised** for agriculture; otherwise limited stabilisation to full stabilisation**
Intermediate storage in liquid form in sludge ponds	Limited stabilisation **
Storage in dewatered form*	Dependent on the type of sludge conditioning; limited stabilisation to complete stabilisation**
Utilisation/storage in dried form*	Limited stabilisation to complete stabilisation **
Storage following incineration or similar	Stabilisation not absolutely necessary
Storage following mechanical-biological treatment	Stabilisation not absolutely necessary

* Can still only be practised as transitional solution up to 2005 in accordance with the German Technical Directive - Municipal Waste.

** *Achieve the technical stabilisation limit*

*** *In accordance with ATV-DVWK-A 131E, ATV (2000)*

Figure 1. Stabilisation requirements associated with the use of biosolids in Germany (DWA, 2003)

Sweden

In Sweden the application of biosolids on agricultural land is regulated by the Swedish Environmental Protection Agency's regulations on the protection of the environment, in particular the soil, when sewage sludge is used in agriculture, SNFS 1994:2 of 30/05/1994. The order considers the following treatments for stabilisation: "biological, chemical or heat treatment, long-term storage or any other process to significantly reduce the health hazards resulting from its use". The use of untreated sludge is allowed if incorporated in the soil within 24 hours (PURE, 2012). Most biosolids in Sweden are used for the production of "construction soils" and only 10% is applied directly in agricultural land (Hugmark, 2007).

2.4.2.4. North America

United States (US)

In the US the treatment, use and disposal of sewage sludge is regulated at the federal level by the USEPA 40 CFR Part 503 rule (USEPA, 1993) and many states go beyond these "minimum standards" and have additional requirements on management, treatment or testing (NEBRA, 2007). The USEPA also offers the states the option of administering the biosolids program on their behalf if they are able to demonstrate enough regulatory and enforcement capacity (Figure 2). As the NSW guidelines are very similar to the Federal USEPA regulations, we have decided to present additional details on some of the states having a more restrictive regulation in Table 10.

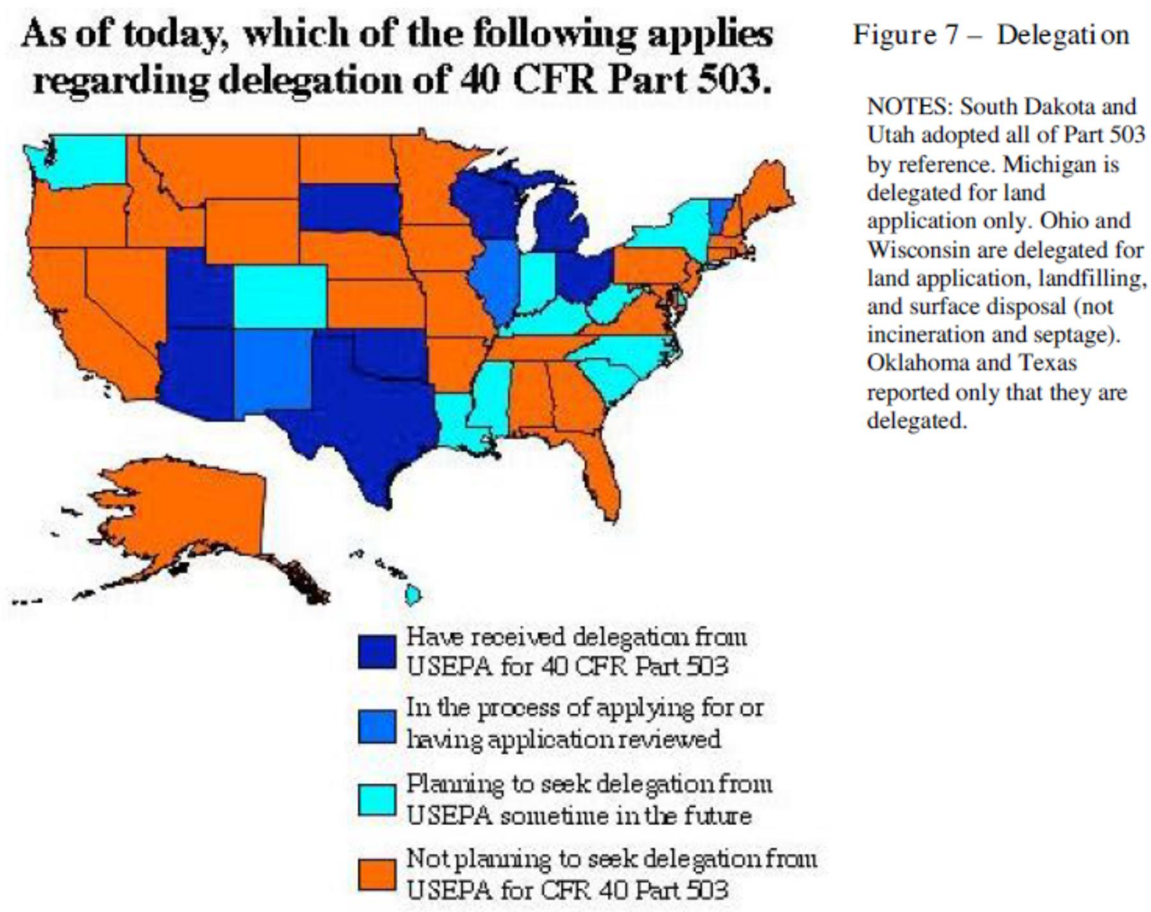

Figure 2. Delegation of biosolids management program to different states in the US

(NEBRA, 2007)

The most recent guidance document from the USEPA in relation to biosolids stability indicates the need to meet the VAR separately from the pathogen reduction requirements, effectively meaning that the achievement of the VAR does not guarantee achievement of pathogen reduction (USEPA, 2003). While the NSW guidelines provide details of the VAR measures for all stability qualities, additional microbiological validation of the treatment performance is only needed for class A. However, approved technologies for the production of class B products need to ensure a geometric mean fecal coliform density lower than 2 million Most probable Number (MPN) per gram of biosolids produced (dry weight). Class A needs to meet the VAR and achieve the following microbiological standards:

- < 1000 fecal coliform MPN/g (dry weight) or < 3 Samonellae MPN /4g (dry weight)
- < 1 PFU enterovirus/ 4g (dry weight)
- < 1 viable helminth ova/ 4g (dry weight

The last independent review of the biosolids management program in the US conducted by the National Research Council (NRC) in 2002 concluded that: ñ*There is no documented scientific evidence that the Part 503 rule has failed to protect public health*ò (NRC, 2002). However, the same report recommends the use of risk assessments to supplement the technological approach to establishing biosolids pathogens regulatory criteria, improving compliance monitoring of the standards and assessing the reliability of the different biosolids treatment processes to comply with the regulations. All of these recommendations are associated with the achievement of stability criteria not only from the microbiological perspective but the other quality features that biosolids products need to exhibit such as the absence of nuisance odour emissions which is acknowledged as a critical parameter to be reduced in the light of public concern and public health. The NRC review states: **"*Sewage sludge treatment technology not only provides the primary mechanism for pathogen reduction and the necessary stabilisation to reduce biosolids attraction as a food source for vectors but also provides the means to reduce odors and related public nuisance and public health concerns*".**

The current regulations have served to protect human health and the environment effectively but have been partially ineffective to address community concerns on ÷stabilityô issues associated with biosolids particularly odour emissions. Many projects in the last decade have been undertaken to address this. Two projects from the Water Environment and Reuse Foundation (WERF) are of particular relevance to this review: the odour emissions project (Higgins and Murthy, 2015) and the high quality biosolids project (WERF, 2016). The former project will be covered in detail in chapter 4 while more details are provided about the latter in this section. The ñHigh Quality Biosolidsò project aims to guide utilities, especially in an urban context, on how to go beyond regulatory compliance to produce biosolids product fit for different markets. This acknowledges that biosolids quality is much more than pathogens and contaminants and that odour and transportability need to be included into the mix to improve the ÷userôs experienceô This project draws from the recent successful experience of the District of Columbia Water and Sewer Authority (DC Water) where upgrading the existing infrastructure, beyond minimum regulatory standards, achieved new levels of operational excellence including the production of a new product named Bloom®, a reduction of 50% on the amount of produced biosolids, the generation of 13 MW of renewable energy and millions of dollars in annual savings for the municipality (Schafer et al., 2013). This represents a step forward in the valorisation chain of wastewater solids and goes beyond the traditional ÷Good Practiceô approach pursued by many municipalities in the US during the last 10 years (NBP, 2005).

Table 10. Comparison of practices in different USA states and NSW (NEBRA, 2007)

Treatment process	Hawaii	Lousiana	New Hampshire	Vermont	Florida	New York	NSW
Anaerobic digestion	Most common use	No data	Common use	Common use	Common use	Most common use	Most common use
Aerobic digestion	Common use	No data	Rarely used	Common use	Most common use	Common use	Most common use
Air Drying	Most common use	No data	Rarely used	Rarely used	No data	Rarely used	Common use
Composting	Common use	No data	Most common use	Most common use	Common use	No data	Common use
Lime stabilisation	Rarely used	No data	Common use	Most common use	Common use	Common use	Common use
Extended aeration	No data	No data	No data	No data	No data	No data	Common use
Comments		Laboratory certification and pathogen testing for all stability grades. Buffer zones to control odours at land application sites	Meeting vector attraction reduction (VAR) by incorporation or injection is not allowed	There is a basic ñno nuisance odoursò provision in the rules, but it is difficult to enforce	Alkaline treated biosolids need to be applied within 24 hours of delivery to site. Temporary storage, stockpiling or staging limited to 7 days, beyond 7 days a permit is needed Application sites need to apply for a permit before biosolids are applied	Voluntary numerical odour emissions limits at land application sites	

Canada

There are no regulations at the national level associated with biosolids management in Canada and this matter is managed by each province or territory independently using different extents and types or regulatory mechanisms (CCME, 2012). The regulatory mechanisms tend to follow a similar approach to the current NSW Biosolids Guidelines with some modifications. For example, in British Columbia, biosolids regulation is covered by the Organic Matter Recycling Regulation which also covers composting and uses a similar A/B classification for the pathogens/contaminants in the biosolids/composting products. A different approach is found in Alberta with a stabilisation grading comprised of only three levels: digested, undigested and wastewater lagoon. An interesting approach is found in the province of Quebec where biosolids are covered by the more general fertilising residuals regulations which uses a similar pathogen and contaminant categories to the NSW Biosolids Guidelines. However, Quebec regulations also include an odour grading category which has been successful to minimise the complaints associated with odour emission on application sites (Beecher, 2010). Table 11 below summarises the different stabilisation practices in selected Canadian provinces and compare them against NSW requirements for the management of biosolids.

Table 11. Comparison of practices in different Canadian provinces states and NSW

(MDDEP, 2008, Government of Alberta, 2001, BC Ministry of Environment, 2002)

Treatment process	Alberta	British Columbia	Quebec	NSW
Anaerobic digestion	Common use	Common use	No data	Most common use
Aerobic digestion	Common use	Common use	No data	Most common use
Air Drying	Common use	Common use	No data	Common use
Composting	Common use	Common use	No data	Common use
Lime stabilisation	No data	Common use	No data	Rarely used
Extended aeration	No data	No data	No data	
Comments	The stabilisation grading in Alberta has 3 categories: digested (anaerobic and aerobic), undigested and wastewater lagoon A new composting facility in Calgary will be treating biosolids from the city to quality A grade compost	Biosolids management is covered under the Organic Matter Recycling Regulation (2002) which includes class A and class B biosolids along with class A and class B compost. It is similar to the NSW guidelines.	Biosolids management is covered under the ñGuidelines for the Beneficial Use of Fertilising Residualsò which include the traditional Pathogen and Contaminant classifications along with an Odour classification.	

3. Suitability of current methods and practices to determine and ensure stability of biosolids

3.1. Chapter summary

The definition of stability (Grade A or B) is associated with two different expected qualities in the final biosolids product:

- Sanitisation or hygienisation (for grade A)
- Reduction of pathogens and putrefaction (for grade B)

Grade A deals with pathogens exclusively and it is considered outside the scope of this report. Different stabilisation processes are able to reduce pathogens but this is different to reducing putrefaction by transforming the organic matter present in the raw sludge. In this chapter, we will focus on Grade B approved processes and the associated Vector Attraction Reduction (VAR) measures included in the Biosolids Guidelines (NSW EPA, 1997) due to the fact that the large majority of biosolids products in NSW are considered grade B (PSD, 2015). The link between stabilisation processes and odour emissions will be dealt with in the next chapter.

Achieving VAR does not mean stability has been achieved, rather achieving stability will achieve VAR (WEF, 2012). We have reviewed the suitability of each of the stabilisation processes and the assessment methods in this chapter with a focus on the VAR measures presented in the NSW Biosolids Guidelines. The irreversible/reversible nature of each stabilisation process and its contribution in moving the raw sewage sludge towards “inertness” present a potential criterion to judge their suitability in ensuring the stability of biosolids. A summary with each stabilisation practice and assessment method is presented below in Table 12.

Table 12. Review of suitability of methods and practices to determine and ensure stability of biosolids

Stabilisation method	Assessment method	Typical regulations for Vector Attraction Reduction options	Theory and basis for regulations	Comments
Anaerobic digestion	Gas production	Not included	High rate of gas production implies degradation of organic matter	Potentially useful for benchmarking of anaerobic digester performance
	VSR	At least 38% reduction in volatile solids during sewage sludge treatment	High values of VSR suggest low remaining amounts of degradable organics. Slow degradation rates of remaining matter expected.	Criteria currently used in the biosolids guidelines. Not enough to guarantee product free of offensive odours
	Additional VSR, (residual biological activity (RBA))	Less than 17% additional volatile solids loss during bench-scale anaerobic batch digestion of the sewage sludge for 40 additional days at 30°C to 37°C (86°F to 99°F)	Low amounts of additional VSR suggest low remaining amounts of degradable organics	Potentially a replacement as a VAR measure as it indicates the potential for further degradation. Limited application from an operational perspective.
	Volatile Fatty Acids (VFAs) in digestate	Not included	High VFA values in digested sludge represent digester instability	Potentially useful but expensive and some issues with repeatability of commercial kits.
	SRT	Not included	Longer SRT enables more organic matter degradation	Needed at least as a complementary measure to ensure a more stable product
	Protein content in dewatered biosolids	Not included	Proteins are precursors for odorous Volatile Organic Sulphur Compounds (VOSCs) produced in the biosolids cake. The levels of bioavailable proteins are affected by cation dosing, digestion, as well as shear and polymer dosage during dewatering	Limited application from an operational perspective.
Aerobic digestion	SOUR	SOUR at 20°C (68°F) is Ò1.5 mg oxygen/hr/g total sewage sludge solids.	Low rates of oxygen uptake suggest low remaining amounts of degradable organics.	Suggested as a more adequate method than VSR for assessing stability. Limitations on the temperature range were it can be applied.
	VSR	At least 38% reduction in volatile solids during sewage sludge treatment	High VSR values indicate low amounts of remaining degradable organics. Slow degradation rates of remaining matter expected.	Criteria currently used in the Biosolids Guidelines. Not enough to guarantee product free of offensive odours
	Additional VSR	Less than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an	Low values of additional VSR suggest low amounts of remaining degradable organics	Potentially a replacement as a VAR measure as it indicates the potential for further degradation. Limited application from an operational perspective.

Stabilisation method	Assessment method	Typical regulations for Vector Attraction Reduction options	Theory and basis for regulations	Comments
		additional 30 days at 20°C (typically used for extended aeration processes).		
Composting	CO_2 evolution	Not included	CO_2 respiration occurs with the aerobic degradation of organic matter. Low respiration rates used as an indicator of stability	Included in the Australian composting standard. Identified as a complementary method for stability assessment.
	O_2 uptake	Not included	High O_2 uptake needed for organic matter degradation and required temperature rise. Low O_2 uptake rates in the curing period imply low remaining degradable organic matter.	
	Treatment duration and temperature	Aerobic treatment of the sewage sludge for at least 14 days at over 40°C (104°F) with an average temperature of over 45°C (113°F)	Most putrescible organic matter is degraded in the first 14 days, while stability is achieved at mesophilic temperatures	Issues associated with ensuring that each particle in the pile receives adequate treatment. Needs to be complemented with an additional assessment method such as CO_2 evolution.
Heat drying	Moisture content	For biosolids which contain stabilised solids only, the proportion of dry solids shall be at least 75%. For biosolids which contain unstabilised solids generated in a primary wastewater treatment process the proportion of dry solids shall be at least 90%.	Moisture content is an indicator of vector attraction compliance, however organic matter is still present and when rewetted may become microbially active, and subsequently produce odours	Heat drying does not degrade organic matter and it is considered as a óreversible stabilisation processô Reduce pathogens only.
Alkali addition	pH	Addition of sufficient alkali to raise the pH to at least 12 at 25°C (77°F) and maintain a pH Ó12 for 2 hours and a pHÓ11.5 for 22 more hours	Bacteria and viruses are reduced significantly a pH higher than 12	Alkali addition does not degrade organic matter and it is considered as a óreversible stabilisation processô Reduce pathogens only.
	pH change with storage			
	Moisture	Not included	Lower levels of moisture reduce pathogen count	
	Ammonia evolution	Not included	Ammonia acts as a bactericidal in the solid matrix	
	Temperature	See pH above	Increased temperatures improve the microbial inactivation/sterilisation	

3.2. Biological, irreversible, long-term and permanent stabilisation processes

3.2.1. Anaerobic digestion

Different studies have shown to what extent the concentration of pathogens in raw sewage sludge is reduced when treated using conventional mesophilic anaerobic digestion (Sidhu and Toze, 2009, Gantzer et al., 2001). The first long term study in the US showing the benefits of the USEPA 40 CFR 503 rule after its enaction (Pepper et al., 2010) showed the impact of mesophilic anaerobic digestion to the final concentration of *as "significantly lower than before the promulgation of the Rule, suggesting better treatment and increased treatment removal of coliforms*". These results are relevant for the quality grading of biosolids in NSW, especially Grade B biosolids, as the current guidelines don't specify any minimum treatment requirements beyond the VAR measures.Rhodes et al. (2015) work on Grade B biosolids supported the measurement of fecal coliforms in the digested sludge to indicate the reduction of some pathogens but warned on the general use of fecal organisms to predict the presence and levels of Giardia (oo) cysts and Cryptosporidium spp. in the digested sludge. For Grade B biosolids, airborne exposure represents the highest public risk of infection to the public when they are applied on land and a robust stabilisation process is deemed to be more effective than community separation distances to reduce this risk, especially when norovirus are included in the assessment (Viau et al., 2011).

Most of the recent developments on stability associated with mesophilic anaerobic digestion are related to the way the process can be modified to minimise odour nuisance (Higgins and Murthy, 2015). Less attention has been paid to the use of VSR, or the level at which it should be set, to ensure the stability of the digestate. The technical document presented by Farrell (1992) on the scientific basis of the proposed regulation at the time (USEPA, 1993) in relation to the use of volatile solids reduction as a vector attraction reduction measure for anaerobic digestion includes the following: *"If the sludge volatile solids content has been reduced 38% by anaerobic or aerobic or chemical oxidation, it is presumed to be adequately reduced in vector attraction. This requirement, which is the same as was used in "Criteria", was drawn from the Water Pollution Control Federation Manual of Practice No. 8 (WPCF, 1967). The selection was largely judgemental but has been reinforced by 9 years of usage under the present regulation".*

The use of a relative value for stabilisation neglects the fact that VS concentrations in the raw sludge depend on the catchment where the wastewater treatment plant (WWTP) is located. As shown in Figure 3 for primary sludge (VSR is lower when a primary and waste activated sludge mix is digested), at high VS concentrations in the feed (85%) the VSR threshold will be achieved at low SRT requirements and the digested sludge will have a higher risk of being odorous. At the other extreme, low VS concentrations in the feed sludge will require higher SRT requirements to achieve the same VSR threshold. This is particularly relevant to NSW as many of the biosolids treatment facilities in the State are currently processing primary sludge with VS concentrations higher than 80%. Acknowledging this fact, Smith (2013) has suggested the development of a 'fit for purpose' formula with the specific physicochemical characteristics of the sludge under consideration to determine an acceptable VSR value. More recent data (Jahn et al., 2016), suggests the threshold in VSR for high solid digestion of municipal sewage sludge should be above 50% when sludge is treated at 37 °C and 15 days of SRT.

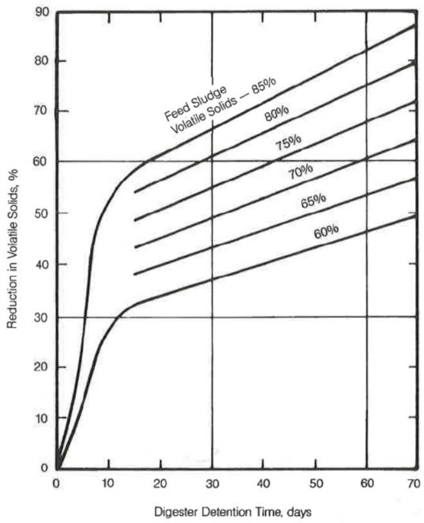

Figure 3. VSR during the digestion of primary sludge at raw sludge VS concentrations and SRT (WEF, 2012)

The effectiveness of using VSR as a VAR measure in anaerobic digestion can be also assessed by measuring the %VS of the digested sludge. (Crosher, 2008) has reported that digested sludge is highly odorous when its VS is over 60-65%. Similar values have been reported elsewhere (PSD, 2009).

Using the %VS in the digested sludge to assess the stability effectiveness of anaerobic digestion is currently used in Germany. Loss of ignition (LOI), which is similar to the VS test, is used to defined the 'technical stability limit' required for different biosolid products applications (Umweltbundesamt, 2013):

- LOI < 50% sludge well stabilised for agriculture and landscaping use
- 50% < LOI < 65% sludge partially stabilised for land reclamation or landfill disposal
- LOI > 65% sludge not yet stabilised for thermal processes

One of the challenges associated with anaerobic digestion facilities is that they have been designed and operated to meet regulatory requirements which does not guarantee that the digestate will meet market or public acceptance requirements (Tsang and Jr., 2005).

Pathogen criteria performance could be improved by including additional details on operational conditions for Grade B biosolids ï which are not included in the current NSW Biosolids Guidelines ï but the stability expectations from the market and the community can only be met if biosolids producers go beyond the regulations for the design and operation of their facilities. For example, Bharambe et al. (2015) reported on the use of recuperative thickening to increase SRT in Bondi WWTP from 15 to 40 days which increased biogas production by 20% and reduced biosolids production and hydrogen sulphide generation by 22% and 80% respectively. Similar SRT values (40 days) are expected to have positive impacts in relation to the stability of the sludge in other NSW plants (Taylor and Batstone, 2015).

Conventional mesophilic anaerobic digestion is still the most popular stabilisation process in NSW for the treatment of raw sewage sludge (PSD, 2015). However, without advanced treatment configurations or by combining anaerobic digestion with other treatment barriers (e.g. composting), it can only produce Grade B biosolids. Due to issues associated with their quality, Grade B biosolids have been banned for agricultural application in some counties in the US and a growing interest in anaerobic digestion processes capable of producing Grade A biosolids has followed (Sobrados-Bernardos and Smith, 2012). Such a ban constitutes a risk for producers and a threat for the overall future beneficial reuse program of biosolids in NSW.

There is also an alternative VAR measure when the VSR>38% criteria canôt be used: *"Anaerobically digested biosolids which do not meet requirement 1 above must have no more than 17% further volatile solids reduction when incubated under anaerobic conditions in a bench scale reactor for an additional 40 days at 30-37° C."* This requirement applies to raw sludge with low values of volatile solids which, after being treated in anaerobic digesters, are unlikely to go beyond the 38% threshold. This is also relevant for previously digested sludges that have been stored in a lagoon for many years and have lost volatile solids significantly (USEPA, 2003). It is considered an effective approach to cater for some instances where the 38% threshold is not achieved (Switzenbaum et al., 2002).

Mesophilic anaerobic digestion is an effective stabilisation process to produce Grade B biosolids if minimum treatment conditions are specified and go beyond VAR measures, the digested sludge presents fecal coliforms readings of less than 2,000,000 MPN/g and process conditions are achieved consistently at the production sites. It also has the potential to produce Grade A biosolids but constraints on the CAPEX required for advanced configurations is a barrier to achieving this goal (Baroldi et al., 2012).

Since the publication of the NSW guidelines, anaerobic digestion has been identified as an indispensable piece of infrastructure in the transition towards a resource recovery approach to process organic residuals in general and sewage sludge in particular (Guest et al., 2009). As a result different studies have been published on advanced digestion configurations which include the use of thermal hydrolysis (Barber, 2016), temperature phased digestion (Riau et al., 2010) and other physical, chemical and biological based technologies (Wang et al., 2008). Different substrates have also been evaluated to improve biogas production in anaerobic digestion in Australia and overseas through co-digestion (Mata-Alvarez et al., 2014, Parry and Fillmore, 2016).

Improving the current NSW guidelines by including more details on the operational conditions, won't be enough to meet market and community acceptance for Grade B products. Having used the USEPA 40 CFR 503 rule (USEPA, 1993) to guide the development of the current NSW Biosolids Guidelines was a necessary, but no sufficient, step in managing biosolids in the State.

The shortcomings presented in this section in relation to the suitability of anaerobic digestion as an effective stabilisation process need to be considered by the regulator and considered in the updated regulatory framework such that market and community concerns are incorporated. This will ensure that the long term success of the biosolids beneficial reuse program is guaranteed (Peccia and Westerhoff, 2015).

3.2.2. Aerobic digestion and extended aeration

Aerobic digestion is the second most popular stabilisation approach in NSW (PSD, 2015) particularly in regional plants (Wilson, 2016) or where the design flow capacity of the treatment plant is less than 50,000 EP (Nowak, 2006). Aerobic digestion needs to comply with the same VAR threshold than anaerobic digestion (VSR >38%) or any of the two alternative measures when VSR is not applicable (e.g. extended aeration). In the first alternative, the sludge should have less than 15% additional volatile solids reduction (AVSR) during bench scale aerobic batch digestion for 30 additional days at 20 °C. In the second alternative, the specific oxygen uptake rate (SOUR) shall be less than 1.5 mg O_2/hour/g total solids at 20 °C (NSW EPA, 1997).

If a sludge is instead considered stable by the absence of noxious odours, longer retention times will be needed to eliminate odour nuisance from aerobically digested sludges, more than double the residence time of many aerobic digesters in use today (USEPA, 2003). In contrast to anaerobic digestion, aerobic digestion doesn't require temperature control, so the residence time needs to be adjusted accordingly to compensate for the changes in temperature to guarantee adequate stabilisation. The recommended operating conditions, not included in current NSW guidelines, for aerobic digestion are described as follows

(USEPA, 2003): *"Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time at a specific temperature. Values for the mean cell residence time and temperature shall be between 40 days at 20 °C and 60 days at 15 °C".*

The thresholds for the three VAR measures chosen by the original USEPA legislation for aerobic digestion rely on work carried out by Koers and Mavinic (1977) , Jeris et al. (1985) and Ahlberg and Boyko (1972). Additional work was carried out after enacting the 40 CFR 503 rule by Farrell et al. (1996) indicating that while these methods were effective to minimise vector attraction, AVSR was a more conservative approach than SOUR. These respirometric techniques rely on the reduction of the metabolic activity of microorganisms in biosolids to assess the potential for further putrefaction. For extended aeration these alternative approaches are important as the WAS, already on endogenous decay mode, will have limitations on achieving a VSR higher than 38% (WEF et al., 2012).

The SOUR of a well-digested sludge will vary from 0.1 to 1 mg O_2/hour/g total solids (WEF et al., 2012) which is lower than the current threshold of 1.5 mg O_2/hour/g total solids. However, Samson and Ekama (2000) have shown that values below 2 mg O_2/hour/g volatile solids will indicate that the sludge has less than 25% of biodegradable particulate organic material content. Switzenbaum et al. (2002), which comprehensively reviewed the different methods to assess stability in biosolids, wrote in relation to the SOUR test: *"In general, the SOUR test was found to be highly useful for evaluating the stability of aerobic solids. The test is simple to conduct and has been widely used. Relatively low levels of variability were found for both intralaboratory and interlaboratory testing".*

The SOUR results are affected by temperature and need to be adjusted accordingly but cannot be used to assess the degree of stabilisation of a biosolids sample if the temperature differs from 20 °C by more than ± 10 °C (USEPA, 2003). Samples also need to be analysed as soon as possible to minimise the development of anaerobic conditions in the sludge and the concentrations should be in the range of 0.5 to 2% TS (Switzenbaum et al., 2002). The updated WA guidelines have chosen the SOUR test over the AVSR test for those aerobically digested sludges unable to achieve a VSR > 38% (DECWA, 2012).

In comparing VSR to the SOUR test, it can be seen that aerobically digested sludges achieve lower VSR values for the same SOUR values when temperature is reduced, requiring additional digestion time to compensate for these lower values.

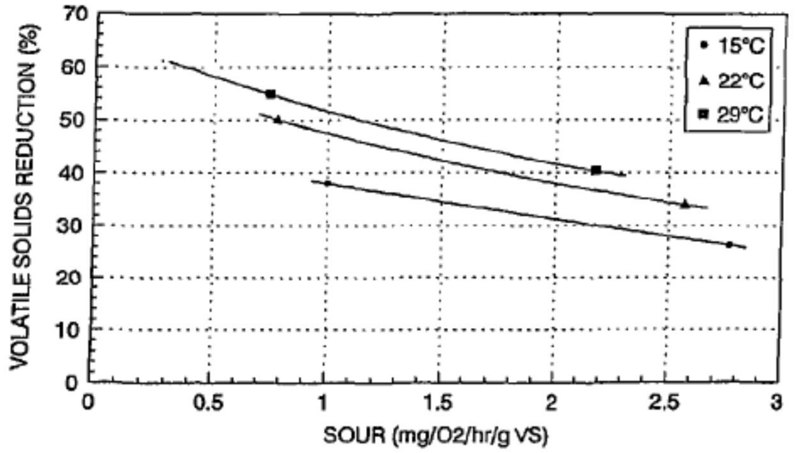

Figure 5—Relationship between volatile solids reduction and specific oxygen uptake rate as affected by temperature, calculated from regression equations.

Figure 4. Relationship between volatile solids reduction and specific oxygen uptake

(Koers and Mavinic, 1977)

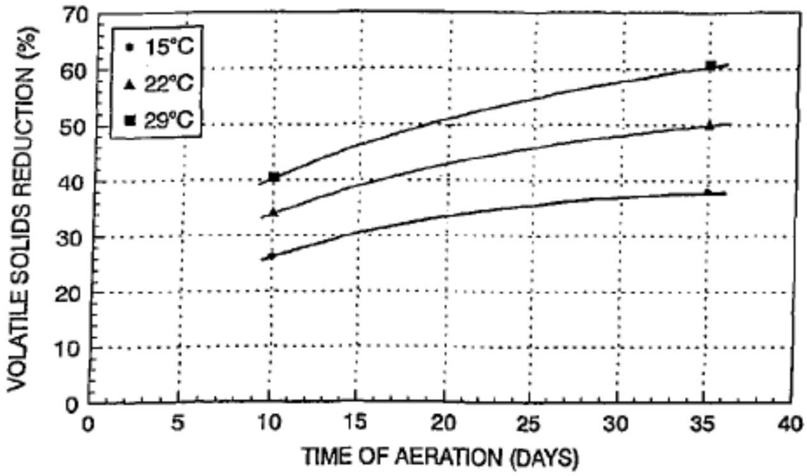

Figure 6—Relationship between volatile solids reduction and time of aeration as affected by temperature, calculated from regression equations.

Figure 5. Relationship between volatile solids reduction and time of aeration

(Koers and Mavinic, 1977)

In contrast to the USEPA guidelines (USEPA, 2003), the current NSW guidelines provide little details on the time and temperature combinations needed in aerobic digestion to ensure an adequate stabilisation is achieved when producing Grade B Biosolids.

3.2.3. Composting

Composting is able to produce biosolids products at the level of quality required by stability Grade A or B (USEPA, 2003). While some reports indicate that composting is not the main biosolids stabilisation process in NSW (PSD, 2015), this process constitutes an important piece in the valorisation of organic residuals in the state as aerobic and anaerobically digested sludges are used as a feedstock in composting facilities around NSW (Wilson, 2016).

Current NSW guidelines provide no details on the process conditions to treat biosolids *beyond the VAR* conditions for composting (NSW EPA, 1997). In contrast, the more recent update from the USEPA regulation (USEPA, 2003) describes composting as a lawful process to produce stability class B biosolids when: *“Using either the within-vessel, static aerated pile, or windrow composting methods, the temperature of the sewage sludge is raised to 40*°C *or higher and remains at 40*°C *or higher for 5 days. For 4 hours during the 5 day period, the temperature in the compost pile exceeds 55*°C*”.*

According to (Farrell, 1992), the rationale to include the 55°C is associated with the need to reduce Ascaris eggs density to reasonable levels according to previous work undertaken by (Brannen et al., 1975). However, this work was undertaken using liquid samples under laboratory conditions which have limitations when applied to windrows, which is the most common technology for composting in NSW. More recent work (Isobaev et al., 2013) have demonstrated that, even for Grade A biosolids where the microbiological conditions are more strict than for Grade B biosolids, the probability of every compost particle achieving the time and temperature conditions required by the regulations in windrows is 93%.

It is common to use the terms óstableô or ómatureô when discussing the quality of compost. However, these quality descriptors are associated with two different stages in the composting process (Wichuk and McCartney, 2013). Stability refers to the reduced microbial activity which renders the product stable and maturity is associated to its suitability for application when the compost is no longer phytotoxic. Substantial progress has been achieved in understanding compost stability and maturity and the updated Australian Standard 4454-2012 for compost, soil conditioners and mulches, provides guidance on the composting of organic residuals, including biosolids (AS 4454, 2012). This standard needs to be considered in the future NSW Biosolids Guidelines and it has been incorporated in the updated WA biosolids guidelines (DECWA, 2012).

There are several different physical, biological and chemical tests to measure compost stability (Switzenbaum et al., 2002) and previous studies have warned on the use of temperature as the only parameter to assess the degree of stability progress during the composting process (Lasaridi et al., 2000, Adani et al., 2006, Wichuk and McCartney, 2013).

However, current VAR regulations indicate the following (NSW EPA, 1997): *"Biosolids shall be treated in an aerobic process for at least 14 days. During that time, the temperature of the biosolids shall be >40°C and the average temperature >45° C. This option relates primarily to composted biosolids".* This requirement may reduce the degree of putrefaction and the level of pathogens to acceptable values but it is not related to the stability and maturity conditions required in a quality product. For example, Li et al. (2004) presented the results of using geosmin to track the progress of stability during sewage sludge composting and found that geosmin production peaks at 60 days just before compost enters the maturation phase. Patureau et al. (2012) has presented the seasonal changes in the temperature profile of composted sewage sludge and found that a stable temperature, usually considered an indicator or compost stability, is achieved after 22 days in Autumn and 25 days in Spring. Due to the issues mentioned before, respirometric methods are usually recommended to assess or complement existing VAR requirements (USEPA, 2003, Switzenbaum et al., 2002).

CO_2 evolution is considered as the most reliable and easy to implement respirometric method to assess biosolids compost stability (Wichuk and McCartney, 2013). Table 13 presents the different values associated with the stability of sewage sludge compost using this parameter (Switzenbaum et al., 2002). Commercial solutions, such as the widely popular colorimetric test Solvita®, can be used to assess the degree of stability of composted biosolids (Gómez et al., 2006) and it is one of the tests included in the current Australian composting standards to assess the degree of stability of composting products (AS 4454, 2012).

Table 13. Stability of biosolids compost based on CO2 evolution (Switzenbaum et al., 2002)

Respiration rate, mg CO_2/g compost-day	Rating	Characteristics
< 2	Very stable	Well cured; no malodorous; earthy odour
2 - 5	Stable	Cured compost; limited odour potential; minimal impact on soil carbon and nitrogen dynamics
5 - 10	Moderately stable	Uncured compost; some malodour potential; addition to soil may immobilise nitrogen; high phytotoxicity potential; not recommended for growing plants from seed.
10 - 20	Unstable compost	Very immature compost; high malodour and phytotoxicity potential, not recommended for growing plants from seed
>20	Very unstable compost	Extremely unstable material; very high malodour and phytotoxicity potential; not recommended for use.

3.3. Chemical, physical, temporal, short-term and reversible stabilisation processes

3.3.1. Lime stabilisation

From the microbiological perspective, lime stabilisation has the ability to produce Grade A or B products (NSW EPA, 1997). Depending on the pH and contact time, the pathogen densities can be reduced to comply with different regulatory limits (Sanin et al., 2011). In addition, the heat produced during the hydrolysis of calcium oxide and the additional bactericidal effect of indigenous ammonia volatilisation contribute to the effectiveness of this stabilisation process (Pecson et al., 2007). The increase in pH discourages the production of hydrogen sulphide in chemical equilibrium and suppresses the degradation of the organics, reducing or eliminating nuisance odours (Sanin et al., 2011).

Volatile solids are not destroyed during the addition of alkali (Sanin et al., 2011). Any contamination or reduction in the pH will resume the degradation of the organic material with the associated release of odorants. If we consider stabilisation from a ôhumificationô perspective, the addition of lime to sewage sludge represents a temporary ôpauseô in the stabilisation continuum.

Previous studies have indicated issues with communities affected by nuisance odours from Grade A and B products from lime stabilisation processes (Laor et al., 2011). For example, Halifax Water stopped temporarily the production of Grade A products after receiving odour complaints associated with the application of their lime amended product (Hydromantis, 2011).

The current VAR measure for lime stabilisation in the NSW Biosolids Guidelines indicates (NSW EPA, 1997): *“The pH value of the biosolids shall be raised to 12 and without the addition of further alkali shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours”.* This measure was included to ensure the pH of the solids matrix is high enough while sludge is being disposed of, even in the case that little insolubilized alkali is left in the solid matrix (Farrell, 1992). However, it has been demonstrated that pH values are likely to remain high for several days when pH is raised to 12.5 (USEPA, 1978).

Similar to the other processes presented in this document it is recommended that additional details are included in the Biosolids Guidelines in relation to the definition of lime stabilisation. The existing USEPA document defines lime stabilisation as (USEPA, 2003): *“Sufficient lime is added to the sewage sludge to raise the pH of the sewage sludge to 12 after 2 hours of contact”.* As lime stabilisation does not reduce volatile solids, it is important to incorporate the lime amended product into the soil before pH falls below 10.5 where is likely to create odour problems (USEPA, 2003).

Original research on lime stabilisation indicated its suitability when there is a need to (USEPA, 1978):

- ñProvide alternate means of sludge treatment during the period when existing sludge handling facilities are out of service for cleaning or repairò
- ñSupplement existing sludge handling facilities due to the loss of fuel supplies or because of excess sludge quantities above designò
- ñUpgrade existing facilities or construct new facilities to improve odour, bacterial and pathogenic organism controlò

Alkali addition is a suitable alternative to treat sewage sludge and has been extremely useful in the past to protect public health; however, it is an end-of-pipe measure. It is the view of the review team that alkali addition has an important role to play as an emergency disposal option to permanent stabilisation processes such as composting, aerobic and anaerobic digestion. A resource recovery approach is less likely to rely on lime stabilisation to treat sewage sludge due to the risk associated with further degradation of organic matter when the pH drops.

3.3.2. Air Drying

Removing moisture from sewage sludge using air drying has shown to reduce the populations of viable bacteria by up to one order of magnitude when the total solids concentration is increased to 90% (Yeager and Ward, 1981).

During lagoon storage, sewage sludge also undergoes further anaerobic and aerobic stabilisation. After a 3 year monitoring program, Pan et al. (2016) reported that a significant amount of influent COD was emitted as methane (43%) and a lower amount (8%) was consumed by aerobic processes.

Current NSW Biosolids Guidelines donôt provide details on the operational conditions required for air drying (NSW EPA, 1997). The most recent regulations from the USEPA (USEPA, 2003) describes this process as follows: *“Sewage sludge is dried on sand beds or on paved or unpaved basins. The sewage sludge dries for a minimum of 3 months, the ambient average daily temperature is above 0°C”.*

As one of the cheapest dewatering methods available for water utilities, air drying is limited by the availability of land which could be a problem in urban centres but not in regional towns (WEF et al., 2012). In NSW air drying is mainly used after the sludge has been stabilised by aerobic or anaerobic digestion (Wilson, 2016) and represent a suitable treatment route when done properly.

4. Stability and odour emissions

4.1. Chapter summary

A wide range of literature focusing on odour emissions from different biosolids stabilisation methods was reviewed, as is reported in Appendix 1 - Literature associated with odours from biosolids. In order to understand nuisance impacts, the odorants, odour emissions and how they are perceived by the community, as well as different analysis methods are briefly outlined in Sections 4.2 and 4.3.

Types of odorants emitted from biosolids depend on stabilisation methods used. However, most emissions typically consist of volatile sulfur compounds, ammonia and other compounds produced from the degradation of organic matter. These odorants can be perceived at low concentrations and have largely offensive odour characters ranging from rotten eggs, rotten vegetables and garbage to rotten fish and ammonia.

From reviewing the literature, odour emissions for the different stabilisation methods are affected by the operation of the stabilisation method; as well as processes upstream and downstream such as sewer catchments, thickeners, dewatering and storage.

Recommendations for assessing biosolids odour emission potential are:

- Thermal drying and alkaline treatment of biosolids should be thought of as hygienisation methods, rather than stabilisation. Biosolids treated using these methods can produce nuisance emissions during storage, transport and land application due to the high remaining organic matter content.
- Meeting VAR based on VSR isn't correlated with a reduction in odour emissions.
- Certain dewatering, conveying and storage approaches can produce additional odour emissions. Therefore the odour potential of the biosolids end product, rather than that of the sludge directly after stabilisation should be measured.
- As the majority of odorants emissions are related to biodegradation of organic matter, VARs such as specific oxygen uptake rate (SOUR), and biochemical methane potential (BMP) are useful tools to measure residual biodegradability and odour potential. However the impact of dewatering, conveying and storage still need to be considered.
- Odour properties of the end product need to be measured, using agreed upon methods. A combination of sensorial and analytical monitoring is recommended. This can be incorporated into acceptable odour quality for different biosolids end uses.

A more holistic approach is needed to develop guidelines for biosolids stabilisation which minimise community nuisance odour impacts. The recommendations to incorporate stability assessment and odour potential into a larger Risk Management approach are outlined in Section 5.

4.2. Introduction to odorants, odour emissions and nuisance impacts

In order to evaluate biosolids stability in terms of odour emissions, the concepts of odour and nuisance emissions need to be defined. Odours, being the human response to odorants, can be measured in different ways. These can be grouped as sensorial approaches, based on classifying how humans respond to different emissions. Or analytical approaches, which is based on the measurement of the odorant concentrations comprising an emission. Various review articles (Gostelow et al., 2001, Brattoli et al., 2011, Laor et al., 2014, Hayes et al., 2014b) have explored various aspects of odour, odorant and odour nuisances so only the general concepts and how they relate to biosolids will be discussed here.

Odorants are compounds that can be smelt. An odour is how we respond to an odorant or mixture of odorants in a gaseous sample. An odour can be described in terms of concentration, intensity, character, hedonic tone and persistency. These dimensions are outlined in Figure 6. Different mixtures of odorants can produce different effects depending on how the odorants interact with our receptors; such effects for mixtures are poorly understood. Not all odours can cause a nuisance, for example some odours are pleasant such as perfumes. The potential for an emission to generate annoyance is typically evaluated according to FIDOL representing Frequency, Intensity, Duration, Offensiveness and Location.

The more frequently someone is exposed to an odour, the more likely it will become an aggravating factor. Higher intensity odours are more likely to generate annoyance. The duration of the exposure time/episode is also linked to odour annoyance. Offensiveness incorporates the hedonic tone (rating of how pleasant or unpleasant) with the odour character. Different people may be offended by different types of odour characters; however some are universal, such as decaying organic matter and manure. The locations in which the odour emissions are perceived also affect the likelihood of an emission being a nuisance. For example urban, high density, with sensitive receptors such as housing, schools and hospitals will generate more annoyance than rural agricultural settings.

A simplified exposure pathway for odour emissions from biosolids, or any odorous material, is shown in Figure 6. The figure shows the large number of factors that influence if odours will be generated and if they will result in odour nuisance. Approaches to preventing odour nuisance from the regulatory perspective rely on simplification of the pathway. The óno justified complaints at fenceô can be difficult to quantify due to its subjectivity, but is simple and low cost. The óno justified complaintô is evaluated by an authorised inspector who judges the situation. A quantitative approach uses exposure percentiles e.g. 2 Odour units cannot be exceeded 98 % of the time. This approach provides a target for utilities, however can be difficult to enforce due to the allowable emissions 2% of the time. In addition dose-response relationships are difficult to predict (Schulz and van Harreveld, 1996).

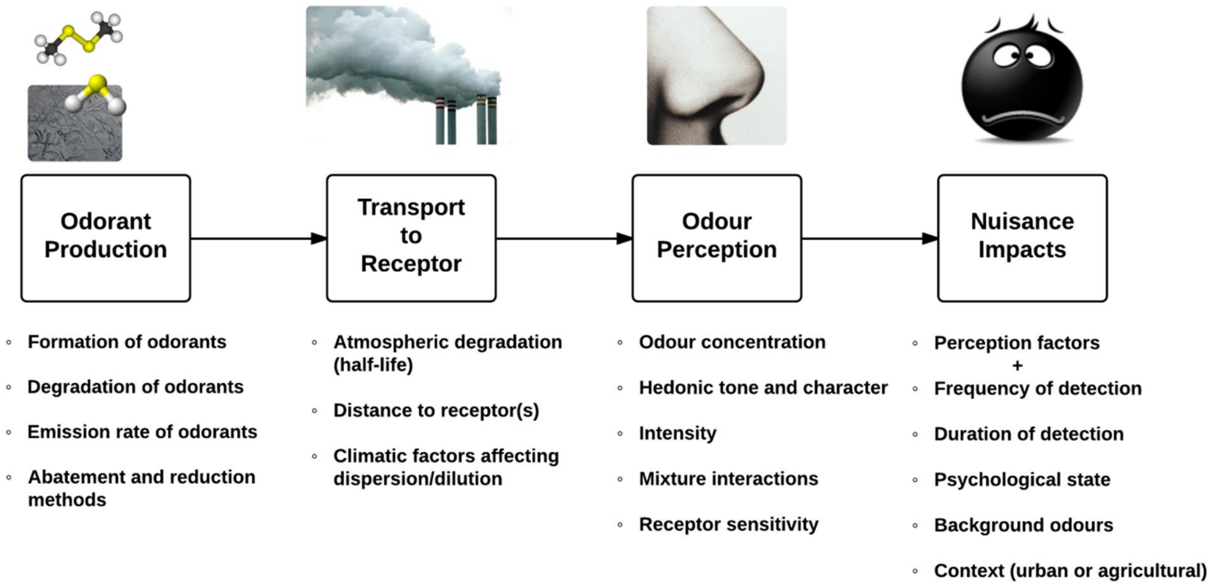

Figure 6. Factors affecting whether nuisance odour impacts will occur. The pathway includes factors affecting odorant production, transport to receptors, receptor odour perception and reaction.

4.3. Odour and odorant analysis

Methods used to sample emissions need to be standardised in order to compare different studies/results. Some sampling methods are more suitable for certain applications, commonly used methods are outlined in Table 14. Flux hoods, wind tunnels or direct sampling methods are more applicable for use in dispersion modelling as they measure a flux or actual concentration. However headspace is widely used to measure the odour potential of biosolids being stored, mostly applicable to anaerobically digested sludge.

There is a need to benchmark the sampling methods used for odorant and odour measurements. The analysis of the generated emissions can be benchmarked by either reference to standards for odorant analysis or inter-lab comparison, panellist selection, humidity normalisation for odour analysis. However, different sampling methods can generate very different emissions, representing different situations. For example wind-tunnels simulate emissions produced in high wind situations, the resultant emissions are therefore not suitable to compare with ambient emissions.

Table 14. Methods used for sampling, concentrating and analysing emissions from biosolids. (Gostelow et al., 2001, Brattoli et al., 2011, Laor et al., 2014, Hayes et al., 2014b)

Method	Description/Typical application
Sampling	
Direct sampling	Ambient or process (pipeline) emissions are captured for analysis
Hood sampling	Emissions generated by a material are captured in a static hood
Flux hood sampling	Emissions are generated by low velocity gas sweeping the material surface in a hood, usually to generate emissions from liquid or porous solids
Wind tunnel sampling	Emissions are generated by high velocity gas, to simulate wind, stripping the material surface, usually used to generated emissions from liquid or solids
Headspace sampling	The headspace of incubated material is sampled, can be liquid or solids
Concentrating/Handling samples for analytical methods	
Sorbent tubes	Compounds are deposited onto solid adsorbents
Solid Phase Micro-Extraction (SPME)	Compounds are deposited onto fibres
Cryogenic/thermal deposition	Compounds are deposited onto cold traps
Analytical methods	
Gas Chromatography + Detector (MS, FPD, FID, SCD + other)	Common method for the analysis of emission samples or concentrated samples. Needs suitable choice of detector, can be integrated with cryogenic/thermal deposition. Can be integrated with ODP (see below)
Specific sensors	Analysis of emission samples for specific analytes, may be affected by non-specific compounds and environmental conditions, can be used onsite. e.g. Jerome for H_2S
Draegar tubes (colorimetry)	Analysis of emission samples for specific analytes or compound groups, typically not very sensitive
E-noses	Analysis of emission samples, may be installed onsite for direct sampling, may be affected by non-specific compounds and environmental conditions, and may be subject to drift overtime.
Sensorial methods	
Concentration	Strength of the odour, measured by diluting the sample until 50% of a panel can't detect it, referred to as dilution olfactometry. The measure is the amount the sample must be diluted, presented as odour units per volume (OU/m^3)
Intensity	Represented using a subjective category scale (i.e. faint – moderate – strong), magnitude estimates (i.e. odour A is twice as strong as odour B) or reference to a specific odorant. Intensity (I) is related to odour concentration (C) according to Stevens Law $I = k\,C^{n}$ where n and k are constants
Character	Subjective description of what the odour smells like
Hedonic tone	Subjective degree of pleasantness or unpleasantness associated with an odour. Measured according to a numeric scale
Persistence	Property of an odour relating to the relationship between the odour concentration and dilution factor for supra threshold values. Percentage of the community/panel that detects the odour at different dilution factors
Combined	
Odour detection port (ODP)	A detection port is added to a GC-MS setup, leading to GC-MS/O. The output from the GC is split so one leads to the MS and the other is sniffed by a trained panellist. Intensity and odour character are described for odour peaks throughout the elution time. Identifies sensorially important odorants in a gas mixture

4.4. Relationships between stabilisation methods and odour emissions

4.4.1. Anaerobic digestion

Anaerobic digestion of biosolids had the largest amount of resources reviewed for the stabilisation methods. The majority are based on work begun by the WERF ñIdentifying and Controlling Odour in the Municipal Wastewater Environmentò series of reports. From reviewing the available research no single operational parameter can predict biosolids odour. While general trends have been identified, itõs likely that a large number of interrelated factors are responsible for producing conditions where odours could be formed, dependant on microbial communities

While volatile sulfur compounds are the major compounds associated with odorous emissions from anaerobically stabilised biosolids, other commonly detected classes are amines, aromatics, ketones and terpenes. Ammonia and hydrogen sulfide are common odorants at wastewater treatment plants, however werenõt always included in emission monitoring. The majority of the literature reviewed used the headspace method for sampling and measured only Methyl mercaptan (MT) and Dimethl suldife (DMS), commonly reported as Total Volatile Organic Sulphur Compounds (TVOSC). A major limitation in odour monitoring is ignoring other odorants such as other sulfur compounds or volatile organic compounds. While the sulfur compounds, due to their low odour threshold and high concentrations, are demonstrably very important sensorially, other odorants such as ammonia, p-cresol, indole and trimethyl amine can contribute to the odour emissions due to their character as being ôfaecalö or ôfishyö

Odorous compounds are typically produced from the degradation of organic matter, such as proteins in the case of volatile sulfur compounds. Therefore biosolids processing will implicitly affect resultant odours. However some biosolids odorants that have been identified in the literature are attributed to different wastewater sources (catchments) or treatment processes in the plants. See Appendix 1.2 for more detail on odorants from anaerobic digestion.

The main findings of the review of the literature regarding anaerobic digestion are:

- Solids retention time (SRT) has a weak positive correlation to peak headspace TVOSC concentrations. This trend is evident at individual sites, as differences in efficiency, feeds and dewatering and conveying downstream complicate the effect when different sites are compared.
- No correlations between biosolid headspace TVOSC concentrations and volatile solids reduction (VSR) were found. VSR, which measures the bulk reduction in volatile solids, represents the degradation of the readily biodegradable organic

matter, rather than the more recalcitrant proteins (Muller et al., 2007b). The remaining protein content, after digestion, has been suggested as an indicator for the potential production of odours (Adams, 2004).

- Shearing during dewatering and conveying frees labile proteins, which when degraded during storage produce odorous sulfur compounds. Also appears to inhibit methanogen activity. High speed centrifuges have greater shear, and therefore emissions compared to medium or low speed centrifuges. Belt filter presses, even when producing similar Total Solids (TS) concentrations to centrifugally dewatered biosolids produce biosolids with much lower odour potential.
- Higher methanogen activity in biosolids cake reduces peak headspace TVOSC concentrations and alters temporal emission behaviour. Methanogen activity appears to be affected by shearing, cation dosing, temperature and amendments.
- Thermophilic digestion produces a later and lower peak in headspace TVOSC concentrations during storage.
- The addition of more digestion stages offers more control over the digestion process as different vessels can be optimised to favour different degradation stages and the stages can buffer the flows through the system, reducing protein content and resulting in lower emissions.
- Polymer addition is weakly correlated with peak headspace concentration, potentially due to increase in shear force and retention of soluble proteins. In addition, when certain polymers are used in biosolids dewatering, they may degrade during storage producing the odorant trimethylamine.
- Negative correlations between iron content and peak headspace TVOSC concentrations have been reported. The role of iron complexes throughout digestion and dewatering result in the sequestering and subsequent release of proteins.
- Conversely, the use of aluminium salts as a conditioner may reduce polymer requirements and peak headspace TVOSC concentrations.
- Pre-digestion methods have been developed to aid hydrolysis, thereby improving digester performance. Many different approaches have been trialled in recent years, however the odour implications are rarely reported. Pre-treatment processes such as Cambi and Microsludge showed improved biosolids headspace odour emissions. Treatment methods using mechanical pre-treatment, enhanced enzymic hydrolysis and chemical dosing also provided reduction in odour emissions. Improvements in odour emissions due to ultrasonic pre-treatment weren't clear.
- Improvements in odour emissions (odorant and sensorial) with additives may be possible, however require full scale, site specific testing.

The current regulatory settings for biosolids stabilisation using anaerobic digestion are based on the digestion process itself. However, after reviewing the literature on odour emissions from biosolids, the dewatering and conveying processes have the potential to drastically alter the emission potential of the digested sludge. The shearing action of dewatering alters the composition of stabilised sludge, making proteins more bioavailable and resulting in odours, as well as sudden increase (SI) in microbial populations.

Murthy et al. (2004) outlines that processes that achieve greater than 45-50% volatile solids reduction, meeting regulatory requirements, can still produce material with residual biological activity. Proteins are harder to degrade in anaerobic conditions compared to polysaccharides and therefore may be concentrated in the final product; about 40% of the remaining volatile solids may consist of proteins. Solids retention time (SRT) has been found in a few studies to give a weak correlation with biosolids odour emissions (Adams, 2004, Toffey and Higgins, 2007, Adams et al., 2007). However, the relationship is likely affected by site specific differences, such as digester efficiency, feed characteristics and dewatering operation.

Dewatering has been widely identified as a key factor affecting the odour emissions of the dewatered product. Shearing during dewatering affects protein bioavailability, with positive relationships between levels of labile proteins and headspace biosolids emissions being identified. Levels of labile proteins in the biosolids are also affected by chemical dosing.

The Biosolids Odour Reduction RoadMap Decision Tool Research Project funded by WERF provides suggestions on ‘best practices’ to improve odour performance for sites using anaerobic digestion and can be accessed in the following website: http://borr.werf.org/DecisionTool.aspx. It recommends areas to investigate/evaluate current operational conditions, with links to laboratory and field scale studies, which are also included in this literature review. Factors that are suggested to be included in onsite abatement plans are:

- Anaerobic digestion operation and performance
- Iron usage on site, as it can concentrate protein in biosolids
- Shear as it can produce bioavailable proteins
- Onsite storage to exceed peak headspace concentrations

4.4.2. Aerobic digestion

Limited data on emissions from aerobically stabilised biosolids was available, representing either the low odour potential of the systems or a large gap in the knowledge of this technology. Odour emissions associated with aerobic degradation are generally considered to be quite low as volatile organics are broken down and oxidised producing an odourless, hummus like stable product (Metcalf and Eddy, 2003). However, earlier plants appeared to be plagued with poor operation or design of the systems, leading to microaerophilic or anaerobic conditions, producing odorous emissions. Such emissions could occur during digestion, or during the storage of the poorly stabilised product where anaerobic conditions developed. Compounds likely to be formed in anaerobic conditions are volatile fatty acids and alcohols alongside volatile sulfur compounds.

Some links between process operation and odour emissions outlined in Appendix 1.3 were:

- While no clear link was drawn between the use of extended aeration and aerobic digestion and odorous emissions. Biosolids produced from extended aeration appeared to have higher headspace TVOSC concentrations
- In Autothermal Thermophilic Aerobic Digestion (ATAD), the aeration rate needs to be controlled to ensure Oxidation Reduction Potential (ORP) doesn’t drop excessively to produce anaerobic regions, but shouldn’t be extremely high to cause undesirable heat losses.
- Good mixing during aerobic digestion is required to ensure anaerobic regions aren’t produced, leading to nuisance process emissions
- Addition of aerobic digesters after mesophilic anaerobic digestion can reduce peak headspace TVOSC concentrations. Likely due to the reduction in protein levels, which are odour pre-cursors, in the biosolids
- Similar to anaerobic digestion, VSR was not a consistent predictor of odour quality.
- Shear in the dewatering process has been linked to increase emissions from the dewatered product.

However, more research is needed to demonstrate whether biosolids produced using aerobic digestion typically present a high risk of odour impact. Eikum and Paulsrud (1977) suggest that a stable sludge should maintain its characteristic soil odour throughout 14 days of storage, therefore character may be a guideline for stability.

Hartman et al. (1979) suggested that while one of the main benefits of aerobic digestion is the generation of a non-odorous residue, optimisation of systems for solids reduction has tended to produce odorous products. The paper claims that specific oxygen uptake rate (SOUR), nitrate concentration and VSR weren’t adequate for describing product stability. Instead, suggesting that where non odorous products are required, the hydraulic detention time should be based on the desired product stability and the volatile solids concentration in the feed. However, this view neglects to take into account the effect of downstream processing (dewatering, conveying, storage).

4.4.3. Composting

The composting process can have a high odour nuisance potential due to the aeration process and exposed surfaces. However the final product, due to the humification process that takes place during composting, should have low odour. Odour properties of the final product could even be used as a quality measure to ensure stabilisation.

Odorants released during the composting process are from the degradation of organic matter or introduced with bulking agents added for moisture control and to promote air dispersion. Each stage of the composting process is characterised by different odour descriptors correlating with the presence of expected odorants. For example, during the initial activity phase of the composting process, faecal, rotten and fishy odors are observed, due to the presence of VFAs, alcohols, aldehydes, ketones and volatile sulfur compounds produced from the incomplete degradation of the high levels of organic matter present. Odour descriptors of the later stages, during compost maturation, are more earthy and musty, signalling the reduction in readily digestible organic matter and a óstableô product. See Appendix 1.4 for more detail.

The history of the sludge being composted appeared to affect odours emitted during the composting process, e.g. more sulfur compounds were emitted from biosolids compared to other feedstocks due to the greater protein content. However, a shortcoming of the studied literature was the lack of information concerning the source and previous processing of biosolids. For example Van Durme et al. (1992) and Maulini-Duran et al. (2013) disagree with Pagans et al. (2006b) as to whether raw sludge (RS) or anaerobically digested sludge (ADS) produce more emissions. Itôs difficult to draw correlations between the studies as the upstream operational details werenôt recorded.

Typically the material is deemed stabilized when the temperature has decreased after the thermophilic phase, and doesnôt rise again (Baby et al., 2005). This temperature rise wasnôt seen for some biosolids sources that had already been anaerobically digested. This occurs as the digested biosolids lack the required readily digestible organic fraction to cause the temperature increase. It needs to be established if the previous treatment is enough to satisfy stability requirements, particularly for microbial regrowth, or if the stability of the compost requires the temperature increase.

4.4.4. Thermal treatment

In the reviewed literature drying was commonly used alongside other biosolids stabilisation methods. From the literature reviewed there is no mention of stabilisation guidelines, odour standards or process performance targets. See Appendix 1.5 for the full literature review.

The majority (70%) of the papers reviewed characterised or monitored emissions from the drying process itself. As the duration of drying processes are typically quick (< 8hrs) and temperatures high, compounds emitted during drying are those already present in the sludge or abiotically generated. Emissions from the drying process typically contained volatile sulfur compounds and ammonia, while a large range of other Volatile Organic Compounds (VOCs) were characterised in the reviewed studies.

Key findings from the literature review regarding odour emissions from thermal treatment are:

- Final product odours are affected by upstream processing, e.g. VFAs emitted from hydrolysed or undigested origin sludge, trimethyl amine (TMA) from lime stabilised biosolids
- Storage of sludge prior to drying increases VOCs and ammonia emissions. This is likely associated to hydrolysis occurring during storage and the generation of odorous compounds that are subsequently emitted during the drying process..
- The drying process is thought to limit biological activity due to a reduction in hydrolytic action with lower water content. However residual odorous compounds can remain. For example: Digested dried product produced less offensive odours compared to undigested equivalent.
- Wetting and/or land application of hydrolysed, or undigested sludge increases odour production due to high levels of readily degradable organic matter now exposed to microorganisms. This provides additional evidence in relation to considering thermal drying as a hygienisation rather than a stabilisation process.

From the literature reviewed the source of sludge was demonstrated to affect the types of odours emitted from the biosolids product, especially when wetted or applied to land. In order to produce a low odour product, care should be taken to dry sludge with low levels of readily biodegradable material or reduce storage time prior to drying. This will reduce emissions during drying, from the dried product, as well as reducing the potential for microbial growth, and generation of foul odours on wetting and land application of the product.

4.4.5. Liming

Alkaline stabilisation of biosolids uses high pHs to disinfect biosolids. The removal of microbial activity limits the biotic generation of odours. In order to prevent microbial regrowth and the subsequent generation of odorous compounds from the degradation of organic matter, the pH needs to be maintained over time. The current guidelines require the pH to be held at 12 for 2 hours, for grade B biosolids. Therefore good incorporation is needed to ensure complete stabilisation and prevent potential pH decay which leads to Volatile Sulphur Compounds (VSC) emissions.

Odorants such as TMA and ammonia are initially emitted from the alkaline stabilised biosolids, due to the increase in pH. However, sulfur based nuisance emissions are produced from the microbial degradation of organic matter. The microbial activity may not be associated with the initial pathogen loading but rather introduced during handling or storage of the stabilised product. Therefore, stabilisation requirements as well as vector attraction requirements require the ongoing suppression of microbial activity if they contain degradable organic material. As such, lime stabilisation is commonly used after other stabilisation methods such as anaerobic digestion or composting to ensure product safety (Laor et al., 2011).

4.5. Recommendations for best practice

Odours are produced from the degradation of organic matter, therefore a more stable product implies less odours produced. Stabilisation guidelines have been developed in the past to satisfy microbial and vector attraction requirements. While odour emissions are explicitly linked to both requirements, a low odour product requires further stabilisation. This is linked to the definition of stabilisation itself, where stable means ‘no or limited change’

Current stabilisation options for Grade A biosolids using thermal treatment, or high pH and high temperature processes are based on hygienisation, as they only reduce the pathogenic microbial load. From an odour perspective this is insufficient as the whole biosolids management chain needs to be considered. While initial pathogenic microbial load is reduced using hygienisation approaches. Due to the presence of organic matter, microbial contamination will occur during storage, transport or land application resulting in the generation of nuisance emissions. Requirements for water content of 75% for dried ‘stabilised’ biosolids do not specify what degree of stabilisation is needed in the ‘stabilised’ before drying. As shown in the literature odorants present in the sludge prior to drying are not all removed, while even sludge stabilised using anaerobic digestion can emit odorous emissions when wetting or during land application.

Specifically for alkaline stabilisation, requirements for the incorporation/mixing of lime should be defined, as high doses and good incorporation would reduce the likelihood of microbial regrowth exceeding the prescribed holding times of 22hrs to 72hrs for Grade B and Grade A biosolids.

The VAR requirements are more aligned with stabilisation. They require reductions in volatile solids, low residual biodegradability and limiting the potential for microbial regrowth (pH, and water content). The relationship between odour emissions and the current assessment methods and regulations for vector attraction reduction requirements in the current ‘biosolids guidelines’ are summarised in Table 15.

A limitation of the current guidelines is that odour itself is not a specific measure. While the current guidelines require Grade B biosolids to “not exhibit offensive odours”, what is classified as an offensive odour is not established. As seen in the literature many factors associated with biosolids processing affect odour emissions. Therefore, in order to protect the community from nuisance odours, the odour quality of the produced biosolids should be incorporated into the guidelines.

Guidelines should specify sampling approaches and target odorants or sensorial properties for each stabilisation method in order to meet acceptable odour quality requirements. Acceptable odour quality requirements can be specified for certain applications, allowing biosolids processing to be tailored for end-use. For example, the land application of biosolids in sensitive areas, such as dense urban populations, should have stricter odour quality requirements. This process will acknowledge the link between emissions and receptors, which leads to nuisance emissions. In addition, this approach is in agreement with facility licence agreements that “Odours offensive to the senses of human beings must not be discharged beyond the boundaries of the premises” under the State Environment Protection Policy (Air Quality Management)(SEPP), of the Environment Protection Act 1970. Methods for using a risk management approach to management biosolids and potential nuisance emissions are discussed in Section 5.

Methods of evaluating odour quality could be based on analytical (odorant concentrations) or sensorial methods (how people perceive odours). A combination of both of these is recommended

- Concentrations of key odorants emitted from biosolids could be monitored analytically using standardised sampling methods such as fluxhoods or headspace methods. Typical odorants typical for each stabilisation method would need to be lower than a certain level for different biosolids applications. Such an approach has been demonstrated in certain areas of Japan under the “Offensive Odour Law” initiated in 1972, where concentration limits for 22 odorous compounds have been set, requiring odorant concentrations in air and water to not exceed those levels. While at a much larger scale compared to biosolids odour quality, the Japanese example demonstrates precedence in the regulations based on odorant concentration.

- Sensorial methods could also be used alongside analytical monitoring of odorants to ensure key odorants were being controlled. Identification of intensity, hedonic tone and odour character of the biosolids product could be used onsite as part of regular performance monitoring. The intensity, hedonic tone and character can be assessed using Odour profiling method (OPM) the methodology of which is similar to the 2170 Flavour Profile Analysis from “Standard Methods for the Examination of Water and Wastewater” from American Public Health Association. Intensity, especially when coupled with hedonic tone and odour character is a better indicator of nuisance emissions compared to odour concentration. In addition, the emissions persistence, which refers to how emissions intensity changes with dilution, can be measured and incorporated into dispersion models.
- Another approach is using odour character. The Quebec guidelines for the ‘Beneficial use of fertiliser residuals’ require biosolids to be classified according to odour category where the odours are compared to other offensive manure types. e.g “low odour: odour less than solid dairy cattle manure” to “out of category: odour greater than hog slurry”. The categories dictate suitable uses for biosolids (Beecher, 2010).
- Odour units or odour concentrations (OU/m^3) are widely used in odour regulation, many facilities under their licenses with the EPA have requirements for a limit of odour units to be emitted from the site boundary for a certain percent of the time. However, links between odour concentration and nuisance impacts, hedonic tone or process operation are often unclear. In addition, odour concentration measurements are expensive and time consuming requiring a panel of minimum six people. Therefore odour concentration measurements are recommended only as a tool to abide by current regulations or to initially rank biosolids odour quality.

The classification of biosolids emissions into categories depending on odour properties (sensorial and/or analytical) could be used to inform suitable biosolids re-use options. Suitable thresholds for biosolids odour quality categories would need to be developed with consultation with utilities, community and regulators. The use of a risk management approach could simplify this process.

In parallel with the adoption of odour quality requirements of the biosolids product, operational targets for each stabilisation method should be established, which will help utilities meet biosolids odour quality, without being overly prescriptive. The guidelines should suggest additional techniques to meet required odour quality based on the underlying microbial and chemical processes occurring in each stabilisation process. This approach will allow more flexibility between sites, allowing utilities to treat their biosolids to levels suitable to their end use, taking into account site specific factors and existing infrastructure.

The current requirements for VSR in anaerobic and aerobic digestion were not correlated with odour emissions (Table 15). Most of the odorous compounds in biosolids are formed from the degradation of residual proteins. In the case of anaerobic digestion, proteins are more difficult to digest so their degradation is not likely to occur in the current VSR requirements. VSR is affected by variation in the digester influent volatile solids content, and therefore doesn't set a requirement for content of the digested sludge

SRT, like VSR, doesn't take into account the end product quality. However, the general trends are that longer SRTs reduce odour emissions, as odour precursors are reduced (Table 15). As SRT is affected by plant influent, operation and efficiency, relationships with odour emissions weren't detected between different sites. Longer SRTs are recommended to reduce odour potential; however digester efficiency and the effect of downstream processing on odour emissions also need to be taken into account. For example, minimising shear during dewatering and conveying can improve biosolids odour quality and handling properties. This can be achieved through the use of belt filter presses, low speed centrifuges, or systems optimised for low odour (for more information see Appendix 1.2.2.5).

The final product 'stabilisation' can be tested by residual biodegradability tests, however again the effect of downstream processing needs to be considered. For example the tests could be carried out on the dewatered cake or after conveying to understand the contribution of these processes or to predict the odour potential of the product. Options include SOUR for aerobic digestion and Biochemical Methane Potential (BMP) for anaerobically digested solids (Table 15). Additionally, the labile protein content of biosolids has been correlated with headspace emissions from anaerobically digested biosolids, so is an option for a stability measure. Colorimetric methods, based on the Lowry method have been used in the literature; a standard method for labile proteins quantification could be developed.

The recommendations are to consider the whole biosolids management process, from sludge to soil, and focusing on the final product odour properties as well as potential. This will allow utilities flexibility in operating their sites, encompassing the use of new pre-digestion processes, use of amendments as well as combinations of stabilisation technologies. In addition, biosolids can be treated to standards suitable to their final use while taking into account community impact of nuisance emissions. The approach to monitoring of odour quality and other performance parameters throughout biosolids processing can be informed by risk management approaches, which are discussed in the following section.

Table 15. Review of suitability of stability and vector attraction reduction assessment methods

Stabilisation method	Assessment method	Vector Attraction Reduction requirements	Demonstrated in Odour literature?
Anaerobic digestion	Gas production		No demonstrated link in literature
	VSR	At least 38% reduction in volatile solids during sewage sludge treatment	Odour pre-cursors, proteins, typically dominate undigested volatile solids. Need much greater VSR%. Effect of dewatering on freeing (making bioavailable) the un-degraded VS not accounted for. No correlation between VSR% and odour emissions from the biosolids product were noted in any study reviewed (Adams, 2004, Muller et al., 2007b, Toffey and Higgins, 2007).
	Additional VSR, (residual biological activity (RBA))	Anaerobically digested biosolids which do not achieve 38% VSR, must have no more than 17% additional volatile solids loss during bench-scale anaerobic batch digestion of the sewage sludge for 40 additional days at 30°C to 37°C (86°F to 99°F)	No link between RBA and dewatered biosolids headspace sulfur concentrations from samples taken from different sites (Adams, 2004). RBA has been linked to VSR and SRT in lab digesters using the same sludge. Lower headspace TVOSC from sludge with lower RBA, which corresponded to higher TVOSC and longer SRT (Adams et al., 2007)
	VFAs in digester effluent		No correlation between VFAs and headspace emissions of dewatered sludge, may be affected by dewatering (Adams, 2004)
	SRT		Generally longer SRTs produce biosolids with lower headspace sulfur emissions (Adams, 2004, Toffey and Higgins, 2007, Adams et al., 2007). However, relationship is affected by dewatering, conveying and other differences between sites.
	Protein content in dewatered biosolids		Headspace TVOSC generation had a positive correlation with bound EPS. (Adams et al., 2007)
Aerobic digestion	Specific Oxygen Uptake Rate (SOUR)	SOUR shall be is Ò1.5 mg oxygen/hr/g total sewage sludge solids at 20°C (68°F)	Odours index analysis supports that SOUR needs to be adjusted for digestion at different temperatures (Koers and Mavinic, 1977)
	VSR	At least 38% reduction in volatile solids during sewage sludge treatment	High VSR have still been shown to have additional VSR (or RBA). A VSR of 65% resulted in a good quality product with acceptable odours when digested aerobically (Davis, 2012).
	Additional VSR	Aerobically digested biosolids which do not achieve 38% VSR,	No demonstrated link in literature

Stabilisation method	Assessment method	Vector Attraction Reduction requirements	Demonstrated in Odour literature?
		must have no more than 15% further volatile solids reduction when incubated under aerobic conditions in a bench scale reactor for an additional 30 days at 20°C (typically used for extended aeration processes).	
Composting	CO_2 respiration		No demonstrated link in literature
	O_2 uptake		No demonstrated link in literature
	Treatment duration and temperature	Aerobic treatment of the sewage sludge for at least 14 days at over 40°C (104°F) with an average temperature of over 45°C (113°F)	Dependant on sludge type, predigested sludges may not reach required temperatures.
Thermal treatment	Moisture content	For biosolids which contain stabilised solids only, the proportion of dry solids shall be at least 75%. For biosolids which contain unstabilised solids generated in a primary wastewater treatment process the proportion of dry solids shall be at least 90%	Sludge origin is linked to odours from dried biosolids, as high organic matter has a greater tendency for ongoing nuisance odour from dried, re-wetted and land applied biosolids (Sivret et al., 2014, Murthy et al., 2003b)
Alkaline stabilisation	pH	Addition of sufficient alkali to raise the pH to at least 12 at 25°C (77°F) and maintain a pH Ó12 for 2 hours and a pHÓ11.5 for 22 more hours	Lower VSC emissions for higher lime doses
	pH change with storage		Decay of pH leads to generation of VSC emissions
	Moisture		No demonstrated link in literature
	Ammonia evolution		Ammonia isnÕt a dominant odorant
	Temperature		No demonstrated link in literature

5. Frameworks for managing odour, stability and vermin – the use of Risk Assessment (RM) methodology and Environmental Management Systems (EMSs)

5.1. Chapter summary

In the original biosolids management guidelines it was stated:

"These guidelines are a step towards producing revised guidelines based on risk assessment." (NSW EPA, 1997)

Reflecting this aim, this chapter of the review outlines findings, conclusions and recommendations on the applicability of risk assessment and environmental management principles to odour, stability and vermin management. It focuses on Risk Management (RM) and Environmental Management Systems (EMSs) and identifies key documents reviewed and conclusions reached. These arise from an analysis of the literature whose details are presented in Appendix 2, 3, and 4. EMSs are included as well as RM because they provide a larger context within which to apply risk management principles and methods.

We first asked the question to what extent odour analysis and management could fit into a risk assessment and management paradigm? As with water, odour impact analysis seemed fully amenable to risk management tool application. The extent odours constitute a health risk depends greatly on the population under consideration and the odorant concentration. However the ISO 31000 meaning of the word ñriskò can cover odours being unacceptable or otherwise for other reasons because the definition of óriskô is general rather than human health specific:

"Effect of uncertainty on objectives" (ISO, 2009)

A range of risk assessment tools were identified for managing odour risk, notably cause X consequence risk matrix, Environmental risk analysis, HACCP and Fault Tree analysis. To accommodate the use of these tools the use of Environmental Management Systems is proposed in order to provide an overall framework for their application and ensure that institutional arrangements for biosolids management are sound.

The concept of biosolids óstabilityô has long been a vexed issue. A risk management perspective may however offer a solution to defining the concept of stability ï the application of HACCP which was originally developed for managing foods. Food production appears sufficiently analogous to biosolids production and management. If this is accepted then we suggest by analogy that óStableô biosolids be viewed as a short hand for:

"Any biosolids intermediate or final product which is within specification for the proposed or existing, generation to recycling, process train and the applicable critical control point, as determined by objective measurements (e.g. chemical analysis, physical observation)".

This proposed definition is designed to cover biosolids at intermediate stages along the biosolids production and management train as well as end products. Vermin and vector management is an issue which this would also cover and the food literature may provide a rich source of management approaches.

A suggested model for new guidelines which would allow the integration of EMS principles, RM techniques with the range of practical and technical methods already developed e.g. within the 1997 guidelines, is the latest Australian Drinking Water Quality guidelines which incorporates all these features. It is also suggested that the guidelines provide direction of the development and use of conceptual and mechanistic models.

5.2. Reviewing the potential conceptual and operational framework for future biosolids management

In its brief for this review of biosolids management relating to odour, stability and vermin (NSW EPA, 2016a), NSW EPA defined the following primary aims:

1. ñCollect and evaluate available information and research regarding the stability of biosolids materials with particular emphasis on answering the question of what is biosolids stability, and what does it mean for biosolids to be stable?
2. Gather information and report on current policies and practices with regards to stability in other relevant jurisdictions both nationally and internationally and compare and contrast those with the current status in NSW.
3. Review the current methods for determining and ensuring the stability of biosolids in NSW, and provide an assessment and justification on whether or not these methods and practices are suitable.
4. Review the link between biosolids stability and offensive odour. Offensive odours generated by biosolids are commonly linked with unstable biosolids. Do the current stability measures and practices influence the potential for biosolids to generate odours? Are there other methods which are capable of directly assessing biosolids for odour production potential? **Provide recommendations on best practice assessment and management of biosolids to reduce and\or eliminate odours.**
5. Any additional information or work the respondent can undertake and deems appropriate to the review will also be taken into account.

The capability of and practical implications for stakeholders to adopt and apply any recommended strategies will need to be considered by the review.ò

Previous chapters of this review examined the technical side of odour and stability management. This chapter reviews ôframeworkô aspects of management which could inform guideline design. The issues addressed are **<u>bold/underlined</u>** above.

5.3. Focus of this chapter of the review

In the original biosolids management guidelines it was stated:

*“These guidelines are a step towards producing revised guidelines based on risk assessment.” (*NSW EPA, 1997)

Reflecting this aim, this chapter of the review outlines findings, conclusions and recommendations on the applicability of risk assessment and environmental management principles to odour, stability and vermin management. It focuses on Risk Management (RM) and Environmental Management Systems (EMSs) and identifies key documents reviewed and conclusions reached. These arise from an analysis of the literature whose details are presented in Appendix 2, Appendix 2, Appendix 4; and Appendix 4. EMSs are included as well as RM because they provide a larger context within which to apply risk management principles and methods.

This focus is consistent with the fact that the Australian water industry has widely adopted both risk assessment and management principles, and EMS, to guide its other management plans:

ñIn the Australian water industry, risk management and quality management are increasingly being used as a means of assuring drinking water quality by strengthening the focus on more preventive approaches. Some water authorities have implemented management systems based on ISO 9001 (Quality Management), ISO 14001 (Environmental Management), AS/NZS 4360 (Risk Management) or more recently the Hazard Analysis and Critical Control Point (HACCP) system that has been adopted internationally by the food industry.ö (NH&MRC NRMMC, 2004, NH&MRC, 2013).

Further it is understood that the pathogen and toxic chemical review counterparts to this review are looking at managing these contaminants based on risk management principles as well, while the key US industry best practice manual (National Biosolids Partnership, 2005) promotes HACCP style risk assessment and management. The sections below:

- Outlines the significant developments since the 1997 NSW biosolids guidelines were implemented, especially the roll out of Risk Management (RM) and Environmental Management Systems (EMS);
- Identifies key documents and explains why they are critical in WRCõs opinion;

- Discusses how far RM and EMS were assessed to be applicable to the management of odour, stability and vermin management;
- Identifies key barriers to, and caveats on, RM and EMS application;
- Suggests a guideline format which could allow EMS, RM and extensive technical information e.g. as in the 1997 guidelines, to be integrated;
- Provides recommendations for NSW EPA in respect to guideline development;
- Explains how this chapter addresses the tasks in the brief above.

5.4. Developments since 1997

Compared to the 1997 guidelines (NSW EPA, 1997) modern Australian environmental management guidelines tend to be less prescriptive in terms of material quality and place more emphasis on achieving high quality management which addresses Environmental Values. For example between its 1992 and 2000 versions the Australian environmental water management guidelines (ANZECC, 1992, ANZECC and ARMCANZ, 2000) moved from an emphasis on achieving specific water quality objectives focused on analytical measurements toward emphasis on achieving and maintaining agreed ‘Environmental Values’ based on a whole of system analysis such as “healthy ecosystem” or “for public benefit, welfare” (Environment Protection and Heritage Council, 2006). These were to be achieved by applying risk analysis and management principles.

Concurrently, risk assessment and management best practice and the underlying science, have undergone major advances. This can be seen by a comparison of the 1990s/early 2000s (Standards Australia/Standards New Zealand, 2004b, Standards Australia/Standards New Zealand, 2004a) Australian risk management standards with the current ISO based ones (IEC/ISO, 2009, ISO, 2009, Standards Australia and Standards New Zealand, 2009, Standards Australia and Standards New Zealand, 2013). One way this has happened is in the clarification of the functions of different risk management/analysis tools for different purposes e.g. risk identification, control, consequence, evaluation, likelihood and level of risk estimation (e.g. Standards Australia and Standards New Zealand, 2013 Table A1). Many tools are quantitative. Specialised tools can be used estimate risk under both nominal conditions and diverse failure and event scenarios when system behaviour departs from its optimal specifications.

Complementing RM in the field of environmental management has been the roll out of the EMS 14000 standards. These address the complementary need of clarifying how organizations organise their management activities such as monitoring, incident response, performance auditing. Thus EMS provides the complementary institutional environment within which to conduct risk management and rationale for why for example different types of monitoring might be undertaken. Details for what this involved are provided not only by the ISO 14000 standard but also the ISO 9000 Management System (MS) standard. The correspondence between these standards is outlined in various documents (e.g. ISO, 2011 Appendix B1).

As noted above many water industry stakeholders have complemented risk management with EMS and MS procedures. Further in the later 2000s and early 2010s the Water Services Association of Australia sponsored the development of management system frameworks via AQUAL and REQUAL (Davison, 2010, Water Services Association of Australia, 2010). Also NSW EPA extensively promotes EMS use (e.g. NSW EPA, 2016b, NSW EPA, 2015).

In this review we asked the following questions:

- How applicable to management of biosolids odour stability and vermin are RM and EMS methods generally and those applied to water management?
- What caveats apply to such applicability? What difficult issues do EPA need to resolve?
- What logistics issues do new guidelines need to address and how might this occur?

In addition to providing general advice and review examples, this chapter provides recommendations on how EPA might act on this advice. This chapter concludes with an outline of how this chapter of the review addresses EPA's brief.

5.5. Key documents identified and why

Reflecting these developments a number of key documents emerged from this chapter's review (Table 16).

Table 16. Key environmental and related management documents reviewed

Document	Why these are Key/Critical	Citation cross reference
1997 NSW biosolids guidelines	Though outdated, these guidelines are the current industry standard and not to be replaced lightly. So updating needs to retain or adapt their most useful features e.g. references to relevant NSW legislation. The biosolids management industry will likely have their current management documents aligned to these guidelines and altering or enhancing them will take time.	(NSW EPA, 1997)
Australian recycled water guidelines.	Sewage treatment yields biosolids and treated wastewater. Ideally the two processes should be harmonised as they deal with similar contaminants and challenges. Modern recycled water guidelines reflect lessons and conceptual learnt in changing from older style quality objective guides which could be adapted to new biosolids management guidelines, notably the wide adaptation of RM principles and methods.	(Environment Protection and Heritage Council, 2006)
Australian guidelines for fresh and marine water quality	As well as illustrating one approach to the application of RM method application to environmental management, these guidelines elucidate the concept of Environmental Values, and their development and use in stakeholder consultation, the first step in environmental health risk assessment.	(ANZECC and ARMCANZ, 2000)
Australian Drinking water guidelines (ADWG)	As well as illustrating one approach to the application of RM methods to environmental management these guidelines this latest version provides a potential up to date model for new biosolids guidelines. It is structured to capture RM principles, guidance on institutional management, small systems and a range of applied and technical resources. This structure could provide a checklist for a biosolids guideline equivalent. Alternatively in the interests of harmonisation the structure itself could be used.	(NH&MRC, 2013)
ISO 31000 and 31010 standards	The 1997 guidelines state that future biosolids management guidelines would be based on risk management. The ISO and related Australian standards summarize current RM best practice in terms of definitions as tools. The definition of risk is significant as it goes beyond the normal perception of human health risk. In addition to well-known RM tools already applied by the water industry to environmental management e.g. cause X consequence matrix, Environmental Risk Assessment (ERA) and Hazard Analysis and Critical Control Points (HACCP) the RM tool kit includes a variety of scenario analysis tools such as Fault Tree Analysis (FTA) which appear ideal for management of problems such as excess odour generation.	(Standards Australia and Standards New Zealand, 2009, IEC/ISO, 2009, ISO, 2009, Standards Australia and Standards New Zealand, 2013)
ISO 14000 and 9000 standards	An issue not addressed in detail within RM guidelines and standards is the matter of institutional context and responsibilities. The 14000 and 9000 standards address this issue and provide a context within which RM can be applied. The ADWG incorporate many elements derived from these standards. Very usefully organizations with limited resources or who are less familiar with RM methods ISO 14005 provides guidance on a staged roll out.	(ISO, 2011, ISO, 2010, ISO, 2004b, ISO, 2004a) (ISO, 2005, ISO, 2008)
National Manual of Good Practice for Biosolids	This US guidance document illustrates in detail the application of HACCP style risk assessment to biosolids management in particular with stability in mind. It provides a diverse list of critical control points for different biosolids processing trains.	(National Biosolids Partnership, 2005)

5.6. Viability of RM and EMS application of odours, stability and vermin

5.6.1. Odours

We first asked the question to what extent odour analysis and management could fit into a risk assessment and management paradigm? As with water its analysis seemed fully amenable to risk management tool application. It is uncertain to what extent odours constitute a health risk (cf. EnHealth Council, 2012b) and this depends greatly on the population under consideration and the odorant concentration. However the ISO 31000 meaning of the word ñriskò can cover odours being unacceptable or otherwise because the definition of óriskô is general rather than human health specific:

ñEffect of uncertainty on objectivesò (ISO, 2009)

- NOTE 1 An effect is a deviation from the expected positive and/or negative.
- NOTE 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).
- NOTE 3 Risk is often characterized by reference to potential events and consequences or a combination of these.
- NOTE 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood (2.19) of occurrence.

Particularly applicable risk assessment and management tools appear to be as follows:

1. The support/lookup methods (IEC/ISO, 2009 Table A2) to identify potential odour issues which provide standard method for scoping odour related risks;
2. The well-known cause X consequence risk matrix is well proven in the water industry and is a logical first step for screening and prioritizing odour issues to be most carefully monitored and managed;
    - Separately this tool provides a logical starting place for the biosolids management industry to start their assessments with, when moving to a risk management system.
3. Environmental risk analysis (ERA) (National Research Council, 1983, EnHealth Council, 2012b), used widely for toxic chemicals appears applicable for analysing whole of system risk, as a process of identifying and integrating risks (historically human health), dose response and (geography based) exposure assessment leading to risk assessment and from there risk management;
    - An attractive feature of this tool in the scheme is the emphasis placed on developing óreality checksô and documenting óuncertaintiesô i.e. validating the risk model proposed and undertaking uncertainty analysis.

- A further feature of ERA is its emphasis on starting risk management with community and stakeholder consultation. This is consistent with our perception of the need for carefully defining Environmental Values for odour.

4. HACCP which focuses on the commodity (biosolids!) production pathway and is designed to identify critical control points where management such as monitoring can be focused;
5. Scenario analyses such as Fault Tree analysis (Lindhe et al., 2012, IEC/ISO, 2009 Tool B14 in Table A1) appears suited to analysing and predicting management failure modes.

Useful and extensive lists of potential issues and critical control points can be found in the US industry best practice manual (National Biosolids Partnership, 2005). This document also illustrates HACCP well in general.

EnHealth (EnHealth Council, 2012b) has questioned whether ERA can be applied to odours as the latter do not necessarily pose a health ŏhazardô And HACCP was developed with health hazard control, particularly pathogens, in mind. The ISO 31000 standards (Standards Australia and Standards New Zealand, 2009, ISO, 2009) provide a simple way around this impasse. They define hazards effectively as that subclass of risks which impact on human health e.g.:

ñrisk (hazard in the context of physical harm)ò; ñrisk (hazards in some contexts)ò; ñrisk (or hazards in a safety context)ò

Thus for risk analysis purposes at least the question of whether odours pose a hazard or not becomes moot and the focus can move on to odour acceptability (e.g. as set out in IEC/ISO, 2009):

- ñIs the level of risk tolerable or acceptable and does it require further treatment?ò
- ñthe extent and type of risks that are tolerable, and how unacceptable risks are to be treatedò?
- ñthe criteria for deciding when a risk is acceptable and/or tolerableò
- ñminimum acceptable level following a disruptionò
- ñacceptable outage time (MAO) for each process based on the identified consequences and the critical success factors for the functionò
- (whether) ñsocially and politically unacceptableò

The ISO 31000 standards illustrate that risk assessment and management is not a single process but involves a number of complementary activities all of which would be relevant to unacceptable odour risk management. This would seem to demand also the development of a larger framework to locate different odour risk management activities. The US industry guide (National Biosolids Partnership, 2005) in effect proposes a HACCP. However the other applicable tools above go essentially unmentioned except by implication or in respect to specific example e.g. the term óodor eventô is mentioned only once.

To address this, an Environmental Management System (EMS) approach seems warranted. It is important to recognise that both the US guidance and the current NSW document (NSW EPA, 1997) contain many EMA type elements e.g. List possible land types where application appears appropriate; Provides storage advice; Identifies applicable NSW legislation; Provides ways of calculating land application rates; Recommends minimum monitoring regimes and analytes; Identifies the need for records maintenance.

However there is less or no advice on for example organisation responsibilities, organizational biosolids policy, HACCP application, equipment capability and maintenance, user satisfaction, emergency response. Placing risk management within a larger EMS context promises to solve this by acting as an umbrella, providing a logical checklist for new guideline features such as the latter, and promoting continuous improvement.

5.6.2. Stability

The concept of biosolids óstabilityô has long been a vexed issue and this is reflected in the lack of clear definition of what this entails beyond biosolid end use quality criteria such as those in the current guidelines (NSW EPA, 1997). These stabilisation criteria do not address odours produced prior to final recycling or disposal. And depending on subsequent events óstable biosolidsô may become biologically unstable in the sense of emitting offensive odours e.g. when pH changes. The latter are also problematic as they are not linked to odour whose desired levels are, themselves, not spelt out beyond ñnoffensiveò and ñminimisedò and ñnuisance causingò.

A risk management perspective may however offer a solution to defining the concept of stability. HACCP was originally developed for managing foods which like biosolids travel along a chain of stages ï food production and processing. Just like biosolids they run the risk of pathogen and chemical contamination and it was the management of these that HACCP was especially designed for.

In addition like biosolids, foods from their sites of initial production all the way through to their final end uses are only partially stable. When their management e.g. loss of refrigeration; goes out of specification at each Critical Control Point assessed by often simple monitoring (e.g. taste, water content gas production, elevated temperature, storage integrity) they are liable to decompose producing off odours and attracting vermin. Such failure is amenable to identification and management via HACCP determined via HACCP analysis. Further, foods in large quantities even under nominal <u>stable</u> production conditions often emit odours which may be offensive to the community e.g. dairy products. What this suggests by analogy is that ‘Stable’ biosolids are better viewed as a short hand for:

Any biosolids intermediate or final product which is within specification for the proposed or existing, generation to recycling, process train and the applicable critical control point, as determined by objective measurements (e.g. chemical analysis, physical observation).

This proposed definition is designed to cover biosolids at intermediate stages along the biosolids production and management train as well as end products.

5.6.3. Vermin/vector attraction

As with food a HACCP system could provide the basis for recognising when a biosolids train product (intermediate or final) is within or outside specification with regard to vermin attraction, whether the risk of vermin attraction is acceptable or otherwise generally and what the impacts of Critical Control Points (CCPs) being out of specification will be.

5.7. Caveats

In respect to odour management the main caveat seems to be the rational setting of benchmarks for what is tolerable or acceptable. Though odour units have many problems they still seem to be the most objective measurable odour target. To address variations in what is considered tolerable an approach analogous to that used with toxic chemicals might be applied. Setting of benchmarks for pathogen and chemical risk has associated uncertainty. The conventional way to deal with this is to over-engineering of barriers or aim for tighter controls than the average e.g. by including ‘safety factors’ for example in toxicity calculations.

In respect to biosolids stability it remains to be determined to what extent a clarification of terminology and movement to an holistic HACCP type system analysis and management system will address this conceptual problem.

In respect to vermin and vectors it is unclear how high the risk posed is. ERA analysis is probably needed at the least at a desktop top level. And vermin risk might be combined with QMRA as pathogen transfer is central to this issue though nuisance and local ecological impacts must also be considered.

In the US there was clear evidence of the water industry undertaking ‘perception management’ and this being now viewed as ‘greenwashing’. This issue is a concern as it impact negatively on public acceptability of biosolids production, processing trains and end use location. This issue needs to be addressed in guideline development by EPA possibly through community consultation.

5.8. Logistics and format of RM/EMS application

The introduction of RM and EMS will greatly expand the size of any new guidelines. It would also be critical for the movement to such frameworks that this did not sideline the work and experience embodied in older more practice oriented guidelines (NSW EPA, 1997).

A possible way this might be achieved could be to use the format of the current drinking water guidelines (NH&MRC, 2013). This document successfully integrates system and risk management ideas and checklists with extensive technical details on measurement of key analytes.

A further important issue recognised in the drinking water guidelines is the need for less onerous arrangements for smaller operations. These guidelines suggest a community size of < 1000 EP requires special consideration and includes model guidance for such situations.

A related challenge is how to roll out any new radically different guidelines. The water industry again provides a model. Historically it started with qualitative risk assessment which allowed organisations to familiarize themselves with the new systems slowly. Subsequently risk assessment and management became more quantitative as the need for clear targets and use of credible statistics was recognised. More practically ISO 14005 provides specific suggestions on roll out of management systems (ISO, 2010).

In processing biosolids within a new guideline scheme it will be essential to focus on critical issues while still doing credible assessments. Modelling appears the way forward here. This can be conceptual as illustrated by HACCP. The latter might be facilitated by the emerging Bayes Net technology which is well suited to documenting HACCP path construction. BNs best practice (Kragt, 2009, Pollino and Henderson, 2010, Marcot, 2012, Marcot et al., 2006) also provides guidance on how to ensure models are valid. Additionally modelling can be fully mechanistic and quantitative as with air transport modelling which is already promoted for use with odour management (Ormerod, 2001, Luhar et al., 2004a, Luhar et al., 2004b, Hurley et al., 2005, Hurley and Luhar, 2005, Hurley, 2006, Xing et al., 2007, Katestone Environmental Pty Ltd, 2009, Noonan, 2009). The current guidelines (NSW EPA, 1997) do not provide advice on modelling but new guidelines could.

5.9. Conclusions regarding information requested in the brief

5.9.1. Answering the question of what is biosolids stability, and what does it mean for biosolids to be stable

The analysis of the stability concept from the point of view of RM indicated that, like foodstuffs along their production train, there is no single stable state but a series of intermediate and final products corresponding to critical control points along the different processing systems. Each of these products may be definable in terms of its odour, analytical parameters and other attributes depending on the processing system. Optimally, each of these biosolids products would be 'stable' in the same fashion as a food product is along a production chain. Thus Biosolids may be managed via the same HACCP systems approach and stability would equate to the biosolids intermediate or final product being within specifications (e.g. low odour). Similarly departure from specifications would correspond to the concept of unstable biosolids. Food 'stability' provides a near perfect analogy for biosolids 'stability in that foods will 'go off' if correct management is not maintained. Further food, especially in large quantities, will produce unacceptable odours and attract vermin under such circumstances.

5.9.2. Report on current policies and practices with regards to stability in other … jurisdictions .. and compare and contrast .. with .. NSW

The analysis in this chapter indicated that the current NSW biosolids guidelines are based on an older style of environmental quality management, the use of relatively predetermined and rigid quality set of qualitative objectives based on scientific analysis style metrics. This 'magic number' style approach has been found to have drawbacks and has been mostly replaced in the food industry and water management fields by best practice based on RM and EMS application. An illustration of (RM) best practice as applied to biosolids, is the promotion in the USA of HACCP style RM to the whole sludge production, processing, transport storage and recycling system. Adopting RM and EMS would also be in line with water industry production management generally.

5.9.3. Review the current methods for determining and ensuring the stability of biosolids in NSW, and provide an assessment and justification on whether or not these methods and practices are suitable.

The current guidelines do not define stability. There is nothing exceptionable with current assessment technologies. However institutionally they are probably too prescriptive. The challenge then becomes of how to best update biosolids management without rejecting the mostly good information and concepts in the older guidelines. WRC has looked at whether application of RM and EMS can achieve this.

5.9.4. Are there other methods which are capable of directly assessing biosolids for odour production potential? Provide recommendations on best practice assessment and management of biosolids to reduce and\or eliminate odours.

It is suggested that new guidelines more likely to reduce/eliminate odours would be based around RM and EMS principles and tools. This is because the latter are designed to ensure biosolids management would be based on an holistic analysis of different processes and allow, indeed encourage, ongoing improvement in management techniques as well as the introduction of new methods.

5.9.5. Any additional information or work the respondent can undertake and deems appropriate to the review will also be taken into account.

The analysis identified caveats on the applicability of RM and EMS to odours, stability and vermin management, and possible solutions as well. For example odours do not pose a classic health risk. However the modern definition of risk can cover odours and given this RM provides a suite of methods to analyse risks under normal processing conditions as well as when processing is not within specifications. The definition of stability has historically been a vexed one. However by viewing and managing biosolids in a holistic HACCP manner the concept may become a non-issue as HACCP/ERA provides a means for consistently specifying in any given process train what constitutes acceptable (i.e. stable) biosolids. Other risk tools e.g. FTA provide means for exploring process failure modes more systematically than in the past. Vermin risks probably need more work and integrated with microbial risk more generally but some basic research is needed to clarify the extent to which they pose a problem and under what circumstances. Further community engagement looks essential especially given the term ‘biosolids’ reflects a public relations campaign designed to adjust public perceptions and this has caused counter-reactions especially in the US.

5.9.6. The capability of and practical implications for stakeholders to adopt and apply any recommended strategies will need to be considered by the review.”

Key documents in the new generation of RM and EMS which are proposed for providing models address resource limitation and phased guideline introduction.

6. Recommendations

1. **Stability in biosolids could be defined as follows: an irreversible and consistent low rate of biological activity achieved after adequate processing of sewage sludge**. **For management purposes, ‘Stable’ biosolids could be better viewed as an intermediate or final product which is within HACCP based specifications developed for the generation => recycling, process train**. Concurrently, pathogens and chemicals need to be at acceptable levels by the final biosolids user and the EPA. For more details please see section 2.2
   1.1. The EPA should consider anaerobic digestion, aerobic digestion and composting as suitable stabilisation processes for the purposes of improving stability and reducing putrefaction/odour nuisance potential of the untreated sewage sludge.
   1.2. The EPA should consider alkali addition and thermal drying as suitable wastewater solids treatment alternatives but they shouldnôt be considered as óstabilisation processesô. While initial pathogenic microbial load is reduced using hygienisation approaches, due to the presence of organic matter, microbial contamination will occur during storage, transport or land application resulting in the generation of nuisance emissions. The EPA should consider thermal drying and alkali addition as hygienisation and/or emergency processes supporting anaerobic, aerobic and composting routes.
      1.2.1. ñFishyò and ñammoniaò odours are generated during alkaline stabilisation due to the pH increase. While the dose and mixing efficiency are key factors affecting if additional odours will be generated during lime storage. Poor dosing or mixing can result in pockets of biosolids that are still microbiologically active. This microbial activity can lower the pH of the ódisinfectedô pile, encouraging more microbial activity in turn resulting in higher odour emissions. See Appendix 1.6.2 for more information.
      1.2.2. For thermally dried biosolids, microbial activity when stored, wetted, and/or incorporated into soil can produce odours. Drying primary sludge or sludge that had only been digested for short periods of time had a high potential for odours upon storage, while odorants present in the sludge prior to drying are not all removed. Current requirements for water content of 75% for dried óstabilisedô biosolids do not specify what degree of stabilisation should occur. See Appendix 1.5.2 for more information.

2. **Incorporate operational conditions from the National Guidelines and Composting Australian Standard (AS 4454-2012) in the updated version of the NSW Biosolids Guidelines.**
    2.1. The EPA should consider adopting the National Guidelines in relation to the minimum operational standards for Grade B approved processes. This is especially important to guarantee minimum SRT levels in anaerobic digestion as well as aeration requirements (adjusted by seasonality) for aerobic digestion and extended aeration. The inclusion of a minimum digestion SRT in the updated NSW biosolids guidelines could be considered as a positive step to guarantee the minimum pathogen log reduction needed for class B biosolids. However, this change won’t guarantee the production of a stable product (low odour) unless additional conditions, such as a higher SRT value (40 days), or advanced configurations, are considered for conventional anaerobic digesters. See section 3.2 for more details.
    2.2. Incorporate the existing Australian Standard on composting in the drafting of the updated biosolids guidelines and include the CO_2 evolution as a complementary VAR measure to the current temperature-time requirements to ensure the stability of composted biosolids. See section 3.2.3 for more details.
    2.3. These would be complemented by the application of risk management methods and integrated using an ISO 14000/9000 framework.

3. **Develop a ‘Best Practice Manual’ and a ‘Certification Scheme’ in collaboration with stakeholders**
    3.1. Develop a voluntary Best Practice Manual on Biosolids Management and encourage utilities to go beyond compliance. Experiences overseas indicate this could be an avenue to improve the quality of biosolids products in relation to stability. See section 2 for more details.
    3.2. Develop a certification system in collaboration with Farmers, Water Utilities, Academics and Contractors to reward operational excellence. This has been a proactive way to minimise potential issues downstream the supply chain and it is of special importance for those products being grown using biosolids (e.g. wheat, canola). See section 2.4.2 for more details.

4. **Biosolids need to be evaluated on odour quality.** A limitation of the current guidelines is that odour itself is not a specific measure. While the current guidelines require Grade B biosolids to “not exhibit offensive odours”, what is classified as an offensive odour is not established. Its recommended the EPA:

4.1. Create a new ñOdour Gradingò category. This new category will deal with the expectations around biosolids products of having ñacceptable levels of odour emissionsò. The experience from Quebec indicates that such move could help to achieve the ñno offensive odourò condition included in the current guidelines. See section 2.4.1 for more details

4.2. Specify methods for odour quality based on analytical (odorant concentrations) and/or sensorial methods (how people perceive odours). A combination of both of these is recommended.

  4.2.1. Concentrations of key odorants emitted from biosolids could be monitored analytically using standardised sampling methods such as fluxhoods or headspace methods. Typical odorants for each stabilisation method would need to be lower than a certain level for different biosolids applications

  4.2.2. Identification of intensity, hedonic tone and odour character of the biosolids product could be used onsite as part of regular performance monitoring. The Odour Profiling Method is suitable for this, and is adapted from the existing Flavour Profile Analysis Standard Method used for drinking water.

  4.2.3. Odour characters can be classified and communicated by comparison with other materials, e.g. soil, rotten vegetables, or cow manure and pig manure as in the Quebec standards (MDDEP, 2008). Tests of stability can include monitoring how the odour characters and intensities vary with storage time. The performance of aerobic digesters is particularly relevant as the stabilised odour is characteristic of soil, while óunstableô or poorly stabilised sludge has a rotten, putrid odour symptomatic of the production of sulfur compounds, or even volatile fatty compounds for poorly stabilised sludge.

  4.2.4. Odour concentration measurements are recommended only as a tool to abide by current regulations or to initially rank biosolids odour quality, as measurements are expensive, time consuming and their link with nuisance impacts is often unclear.

4.3. Guidelines should specify sampling approaches and target odorants or sensorial properties for each stabilisation method in order to meet acceptable odour quality requirements. Consistency is needed in reporting of odour properties and methods need to be reproducible and accurately represent potential odours.

4.4. If recommendation 4 is not adopted, a new set of Odour Nuisance Reduction (ONR) measures should be included as a minimum. These conditions may be located next to the ñapproved treatment processesò to minimise the risk of óoutrage eventsô during processing, transport and application. For more details See Section 3.2.

5. **Product specifications for biosolids need to be developed holistically by each water utility bearing in mind expected/like subsequent processing transport storage and end-use**. This is due to the wide range of process/transport/storage and final use combinations possible and each water utility should guarantee these product specifications are aligned with the updated EPA guidelines. For more details please see section 2.3.

6. **Refine the existing "Stability Grading" by changing it to a "Pathogen Grading".** This move would be aligned with the National guidelines on Biosolids Management and will enable the regulator to combine the approved processes for Grade B biosolids and VAR measures under one single category to ensure that the pathogen reduction required to protect public health and the environment is effective. Grade A remains as in the current guidelines. See Section 2.4.1 for more details.

7. **Operational targets for each stabilisation method should be established**, which will help utilities meet biosolids stability and odour quality criteria, without being overly prescriptive.
   7.1. Longer SRTs are recommended to reduce odour potential; however digester efficiency and the effect of downstream processing on odour emissions also needs to be taken into account.
   7.2. Minimising shear during dewatering and conveying can improve biosolids odour quality and handling properties. This can be achieved through the use of belt filter presses, low speed centrifuges, or systems optimised for low odour based on low shear, chemical dosing or long digestion times.
   7.3. Specifically for alkaline stabilisation, requirements for the incorporation/mixing of lime should be defined, as high doses and good incorporation would reduce the likelihood of microbial regrowth exceeding the prescribed holding times of 22hrs to 72hrs for Grade B and Grade A biosolids.
   7.4. Targets and monitoring must recognise biosolids heterogeneity and the challenge of ensuring quality measurements are representative

8. **Stabilisation/pathogens/odour measurements should be undertaken on both intermediate and the final biosolids products and need to be site specific**.
   8.1. Tests such as VSR do not represent an appropriate stability measurement of biosolids when anaerobic or aerobic digestion is used. The current level of 38% VSR is easily achieved but the evidence indicates that it is not enough to minimise the risk of producing odorous products. This is further complicated by the impacts

arising from the WWTP catchment which requires the development of site specific baselines. Volatile solids in the final product could be used to indicate the amount of organic matter remaining in the biosolids but it may not guarantee a low odour product in all possible cases. Levels could be defined in the final biosolids product as in the German Standards and additional tests such as protein measurements could also be explored

8.2. The processing of biosolids after digestion needs to be considered by the EPA as it can affect their odour potential. Shearing of biosolids during dewatering and conveying releases labile proteins which, when microbially degraded, produce odorous emissions. See Appendix 1.2.2 for evidence in anaerobically digested biosolids. Wetting, contamination or land application of õhygienisedö biosolids, those that have been limed or thermally dried, can also produce odorous emissions (see Appendix 1.6.2 and 1.5.2)

8.3. Biosolids handling should consider emission temporal trends. Most mesophillically anaerobically stabilised biosolids emitted peak headspace concentrations in the first 3-5 days, therefore the EPA should consider a weekøs storage to minimise high emissions during transportation of the biosolids to land. Iron dosing can also shift the timing of the peak headspace concentration. Site specific understandings are required.

9. **Methods which measure residual biodegradability should be used to rate biosolids on their stability/odour potential.** Residual biodegradability can be measured in a variety of ways, e.g weight loss, CO_2 or CH_4 generation, pH, VSR, oxygen uptake, substrate availability.

9.1. Specific Oxygen uptake rate (SOUR) is recommended for aerobic sludge stabilisation. Itøs thought to be suitable as high microbial activity in biosolids piles typically leads to anaerobic conditions and the formation of sulfur based odorants and ammonia.

9.2. Biochemical methane potential (BMP) can measure residual biodegradability in anaerobic systems.

9.3. High levels of labile (microbially available) proteins in dewatered anaerobically stabilised sludge produce odours as they are degraded. Colorimetric methods, based on the Lowry method have been used in the literature; a standard method for labile proteins quantification could be developed

10. **The new guidelines need to incorporate risk (RM) and environmental management (EMS) approaches**. The NSW EPA 1997 Biosolids Management Guidelines state that they are viewed as an interim document to be replaced in a timely fashion by guidelines based on risk assessment and management principles and methods. This statement was consistent with developments at the time when óRisk Managementô was emerging as the new basis/framework for water management. WRC concurs with this and proposes the next version of the biosolids management guidelines to follow this recommendation.
    - 10.1. Risk management needs to be applied within a wider institutional framework. WRC suggests this can be provided by implementing ISO 14000 and ISO 9000 Environmental /Management Standards. A model for the guideline format for this is provided by the current Australian Drinking Water Guidelines.
    - 10.2. Risk based biosolids guidelines should/need not start from scratch but adapt the risk management methods and concepts developed in the past 20 years which address comparable environmental tasks to biosolids management, particularly guidelines developed for water (ecosystems, bathing, and especially drinking and wastewater and its recycling) and food management.
    - 10.3. EMS can provide a framework for integrating other best practice e.g. AS 4454-2012.

11. **The Biosolids guidelines developed for odour, stability and vermin management need to be well structured.** The format should:
    - 11.1. Be harmonised especially with their wastewater treatment and recycling counterparts. This seems appropriate as wastewater treatment and recycling tend to go hand in hand with biosolids production and reuse.
    - 11.2. Be harmonised with their new chemical and microbiological contaminant guideline counterparts which will likely be environmental risk assessment based as well, wherever appropriate and desirable. Note that the concepts of óodourô and óstabilityô do not fit neatly with older concepts of (human health) risk. However, the ISO 31000 definition of óriskô applies to any perturbation from the normal (environmental) conditions and so is applicable;
    - 11.3. Be designed to promote management of biosolids being undertaken holistically and be continually improved as new information comes to light, without the need for regulator intervention at detailed level:
        - 11.3.1. In addition to applying holistic risk assessment and management tools e.g. HACCP and ERA, the industry standard which seems applicable here is the Environmental Management System series of standard - ISO 14000 and its

more general counterpart the ISO 9000 series. It is already applied to animal faecal waste so applying this to human wastes seems still more reasonable.

11.3.2. Application of ISO 14000 would need to occur at a rate moderated by industry capacity to comply. It would provide a range of additional guidance on biosolids management system and process validation and verification for example. ISO 14005 provides guidance on this.

11.3.3. Usefully there are already HACCP and ERA auditors who could add auditing of biosolids management systems to their inventory.

12. **The guidelines should include strategic/high level biosolids management principles as major initial chapters**. These should include Environmental Values, the use of Environmental Management Systems and Risk Management systems and consultation recommendations:

12.1. Industry risk management based guidelines for water begin with description and clarification of primary management principles. For example the drinking water industry identifies key vulnerabilities and actions for safe water management e.g. microbial hazards and senior management commitment/responsibility.

12.2. Similarly the environmental waters ANZECC guidelines identify primary óEnvironmental Valuesô Many should be transferable directly from the latter documents subject to their applicability to stability, odour and vermin control.

12.3. As with water and food, an holistic view and system analysis should be applied when developing a biosolids and risk management system. In the latter examples this is embodied in the expressions ócatchment to consumerô and ófield to forkô

12.4. This reflects the fact that failure at a critical control point e.g. maturation at plant, can be transmitted along the system e.g. transport malodours. **This** means in practical terms for biosolids, production, transport, further processing and ultimate environmental reuse must be integrated even if different organisations have nominal responsibility for different steps in returning biosolids to the natural environment.

13. **Risk management should be in line with ISO 31000 and employ all appropriate/applicable tools** (ISO 31010). EPA should advise on which tools are appropriate. This does not mean use all tools *per se* but those which address biosolids management needs. The following are a list of risk management tools recommended:

13.1. One or more of each of the following risk management activities:

13.1.1. Lookup/scoping issues tools (e.g. Delphi, formal Brainstorming) to comprehensively scope the issues faced in any particular biosolids management scheme;

13.1.2. Cause X consequence matrix analysis

13.1.3. Function analysis (e.g. HACCP, ERA);

13.1.4. Scenario analysis (e.g. Fault Tree Analysis);

13.1.5. Controls analysis (e.g. Bow-tie);

13.2. One or more tools ñstrongly applicableò addressing the following general activities:

13.2.1. Risk identification (e.g. Delphi);

13.2.2. Consequence assessment (e.g. Event Tree Analysis);

13.2.3. Likelihood assessment (e.g. Fault Tree Analysis);

13.2.4. Level of risk estimation (Probabilistic methods e.g. Monte Carlo);

13.2.5. Risk evaluation (HACCP, Bayesian analysis);

13.2.6. Control analysis (e.g. HACCP).

14. **Bayes Net based analysis to systematically define and quantify variables and issues as far as possible**

14.1. Note that Bayes Net construction and application best practice corresponds to all of the tools above and potentially provides a single platform as well as conceptual framework (Bayesian inference)

14.2. BNs development can be thought of as robust HACCP analysis in that it forces uses to clearly articulate their beliefs and data in respect to biosolids processing, management and failure modes.

15. Biosolids monitoring should be harmonized with and designed to inform Biosolids management, e.g. as illustrated by the enHealth ERA scheme.

15.1. This must be the case under normal operating conditions and during foreseeable deviations from nominal conditions (e.g. hazardous events, change in receiving environment situation)

15.2. Monitoring has a range of different functions and these should be defined.

15.2.1. Within ISO 14000 monitoring can be used for validation, verification and periodic auditing.

15.2.2. In the case of water there are at least 6 different types ï strategic (status and trends, preliminary surveys), compliance (permits and standard achievement), operational (process control, early warning).

15.3. All risk assessment is incomplete and leaves residual uncertainties. In line with ERA guidelines, uncertainty documentation and reality checks should be undertaken when developing a biosolids management system. Such caveats provide the basis for targeting improvements in ongoing management systems e.g. subsequent plan revisions and iterations.

16. **The process of transitioning to the new guidelines can be simplified by using existing tools.** Experience in the water industry has shown that moving from a monitoring objective focus to a management outcome focus paradigm can be resource intensive and take time. Accordingly, EPA should roll out risk/EMS systems in a staged fashion depending on organisation experience and resources. A step by step process for biosolids managers is recommended to achieve this e.g.:
    16.1. Introduce qualitative/semi-quantitative risk assessment based on the HACCP and general matrix approaches. Fix clear vulnerabilities;
    16.2. Develop risk and ISO 14000 management systems reflecting the HACCP system conceptualization. Prioritize vulnerabilities using the matrix approach. Use REQUAL to check ISO 14000 being addressed in principle.
    16.3. Revise system and plans based on quantitative data and assessment.
    16.4. Check all management needs identified in ISO 31000 has been met.
    16.5. Development of full REQUAL style management system.

17. **The review revealed a number of caveats and unresolved issues which EPA should address in new guidelines:**
    17.1. Odour based endpoints are still unclear though models exist. The latterφs use should be clarified (see above for suggested metrics and criteria).
    17.2. Clarification of what óstabilityô entails is needed. This review suggests two complementary definitions(see Recommendation 1).
    17.3. Modelling of risk and environmental processes is becoming more and more routine. EPA should develop a list of recommended modelling tools and the purposes to which they are put e.g. AusPlume. Conversely EPA should identify what is not recommended especially in respect to odour assessment.
    17.4. Vermin pose a clear health risk but this has not been quantified or clearly defined in an ERA fashion. A desktop evaluation is required in the first instance (strategic) based on exposure pathway assessment. EPA should sponsor this.
    17.5. Perceptions of biosolids recycling desirability are extremely varied. EPA should undertake a community consultation to minimize the conflict and controversy. In particular the concerns of óorganicô producers should be explored as they may be outdated or not relevant to the human context or only be applicable to some STPs. ñPerception managementò or the impression this is occuring must be avoided.

17.6. Gaps and scenarios for biosolids management failures are unclear. EPA should develop a series of these to help industry understand vulnerabilities.

17.7. Monitoring requires scientific knowledge based benchmarks. EPA should develop these in concert with industry and other stakeholders.

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1. Appendix 1 - Literature associated with odours from biosolids

1.1. Study scope for each stabilisation method

A large selection of resources was reviewed for the different stabilisation methods focusing on studies which measure odour emissions, analytically or sensorially. Ninety four papers were reviewed measuring odorants and odours associated with the different stabilisation methods. The majority of papers were related to anaerobic digestion, being a focus of the Water Environment Research Foundation (WERF) reports on Identifying and Controlling Odour in the Municipal Wastewater Environment and other associated papers. A variety of sources were reviewed such as journal articles, conference papers and reports and magazines (Figure 7). For the different stabilisation methods typically equal numbers of full-scale and laboratory scale tests and studies were conducted (Figure 8). Full scale studies have the advantage of representing actual operation, while laboratory scale trials enable the impact of individual operational parameters on odour emissions to be determined. Headspace sampling was the most commonly used sampling method for all of the stabilisation methods (Figure 9). Consensus is needed between, and within, the different stabilisation methods in terms of approaches for sampling, analysing and reporting odour emissions. The following section presents the key findings for each stabilisation method.

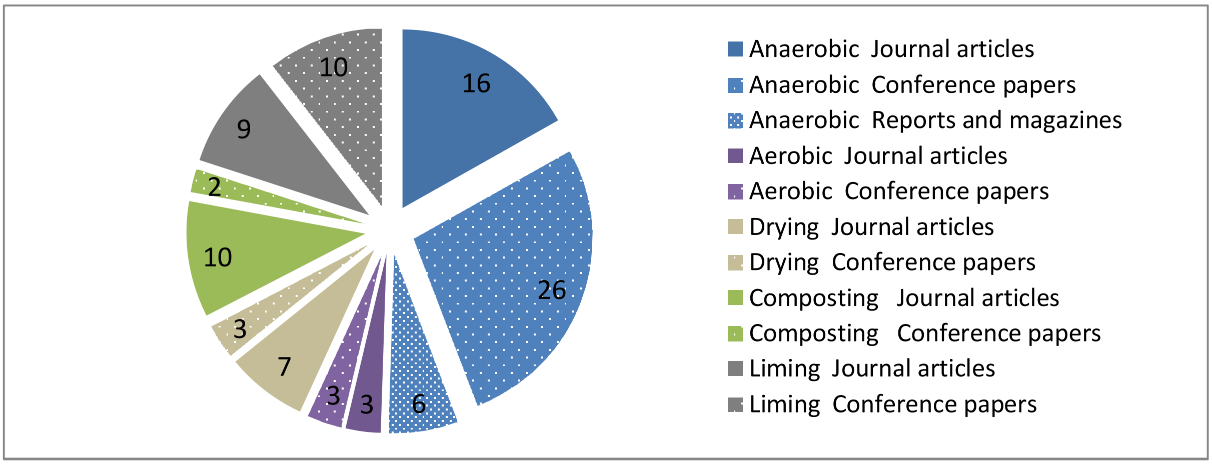

Figure 7. Number of different types of data sources reviewed for each stabilisation methods

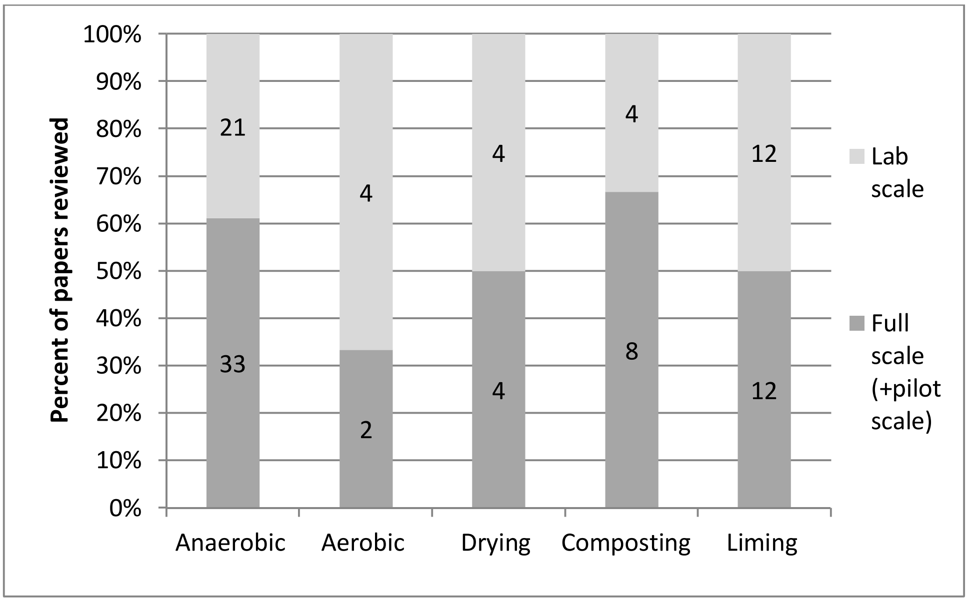

Figure 8. Comparison of the number of papers based on lab scale and/or full scale studies for each stabilisation method

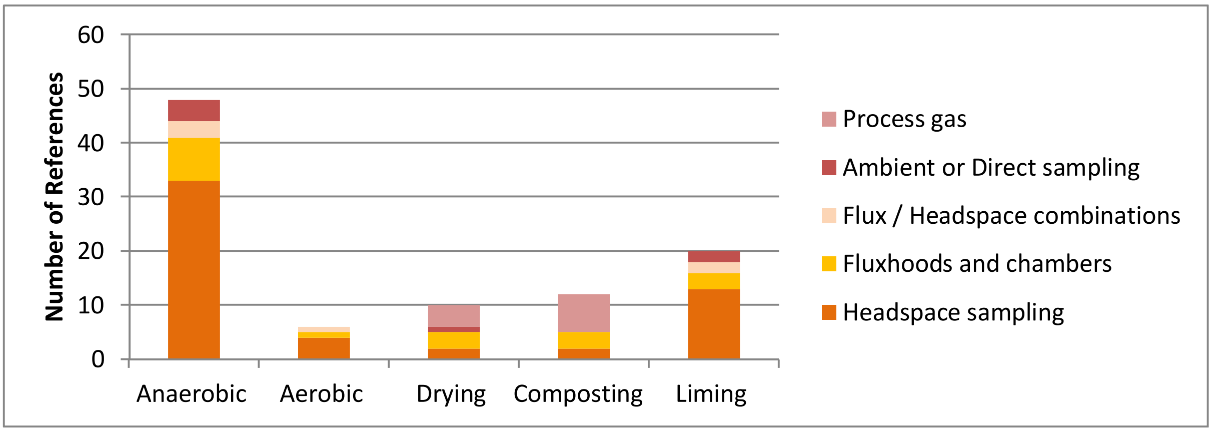

Figure 9. Comparison of the number of reference using different odour sampling methodologies for each stabilisation method

Reporting and communicating odour emissions

The units used to report emissions are another area needing consensus for stability reporting.

Within anaerobic digestion the majority of the studies use headspace sampling as their sampling methodology. While studies have used different analytical instruments to analyse headspace concentrations, the output should be comparable if the instruments are calibrated to standards

However, there are a number of ways headspace concentrations were reported:

- Concentrations of individual compounds; these are most typically MT and DMS, however dimethyl disulphide (DMDS) is also sometimes reported. Units may range from ppm to ug/m^3 however conversion is possible between these.
- Concentrations of total volatile organic sulfur compounds (TVOSC); the majority of the resources report headspace emissions using this method. While being easy to communicate, the grouping losses odorant specific information. Is seen reported in ppmv of TVOSC, mgS/m^3, uLS/L
- Normalised values are typically used when comparing samples with different compositions and to isolate effects such as sample weight, dry solids, or volatile solids. mgS/gVS or mgS/g dry solids

As the majority of the literature is based on comparative studies, no consensus with units was needed e.g lower emissions were noted when SRT was increased or lower shear centrifuges were used. However, there hasn't been consensus as to what concentrations represent an acceptable odour level from headspace sampling of biosolids. Acceptable headspace concentrations of either individual compounds or aggregated values need to be established, linking to exposure assessment. Subsequently, reporting conventions can be established for to allow comparison between studies.

1.2. Anaerobic digestion

Anaerobic digestion of biosolids had the largest amount of resources reviewed for the stabilisation methods. About half were from conference papers, the rest a combination of journal papers, reports and a few magazine articles. The majority are based on work begun by the WERF ñIdentifying and Controlling Odour in the Municipal Wastewater Environmentò series of reports. From reviewing the available research no single operational parameter can predict biosolids odour. While general trends have been identified, itõs likely that a large number of interrelated factors are responsible for producing conditions where odours could be formed, dependant on microbial communities.

Much of the literature (~70%) on odour emission measurements for anaerobically stabilised biosolids have generally been based on headspace concentrations of methyl mercaptan, dimethyl sulfide and dimethyl disulfide represented as total volatile organic sulfur compounds (TVOSC). Other sampling methods used were fluxhoods, flux chambers and an adapted swept headspace method (n=7) and ambient samples (n=4).

The majority of the papers examined emissions generated during the storage of the produced biosolids, fewer evaluated the effect of land application (n=7) and from ambient air near the biosolids processing facilities (n=3). A number of lab scale studies were conducted to evaluate different digester set-ups (multistage, thermophilic etc.) as well as chemical addition. Many studies also evaluated their findings in full scale plants, likely associated with the WERF stage 4 work. This is an important step, as many of the lab-scale findings didnõt apply, or not to the same degree, in the full scale trials.

1.2.1. Odorants identification

While volatile sulfur compounds are the major compounds associated with odorous emissions from anaerobically stabilised biosolids, other commonly detected classes are amines, aromatics, ketones and terpenes. Itõs interesting to note that ammonia, which is widely acknowledged to be emitted from anaerobically stabilised biosolids, due to the degradation of proteins, was only measured in a few studies. Hydrogen sulfide is another odorant which typifies odorous emissions at wastewater treatment plants, like ammonia it was generally needed to be measured using a separate system (e.g Jerome). Of the total number of papers, 25 of them only measured volatile sulfur compounds, while 2 papers only measured sensorial methods (Table 17 and

Table 19).

Table 17. Number of papers measuring VSCs, VOCs and sensorial properties of emissions from anaerobically stabilised biosolids

Measurement focus	Factors measured	Number of papers
VSCs	Select VSCs	31
	Range of VSCs	10
	Only VSCs	25
VOCs	Select VOCs	11
	Range of VOCs	8
Sensorial measures	Only OU	2
	OU	22
	Intensity	7
	Hedonic Tone	5
	Character	6
	Persistence	1
	ODP	1

The resources contributing to Table 18 are those which measured more than just the select volatile sulfur compounds. The majority of the literature reviewed used the headspace method for sampling and measured only MT and DMS, commonly reported as TVOSC. A major limitation is ignoring other odorants such as other sulfur compounds or volatile organic compounds. While the sulfur compounds, due to their low odour threshold and high concentrations, are demonstrably very important sensorially. Other odorants such as ammonia, p-cresol, indole and trimethyl amine can contribute to the odour emissions as is reflected in the typical character of odours being faecal, or fishy in addition to the rotten type odours of the sulfur components.

Odorants associated with anaerobic digestion vary throughout the treatment train. Compounds emitted from the anaerobically digested sludge may be formed during digestion. The dewatering process influences the production and emission of compounds from the dewatered sludge, while storage conditions affect the generation and degradation of compounds as well as their emission rate. The generation conditions and pre-cursors of commonly detected odorants from anaerobically stabilised biosolids are shown in

Table 19.

Table 18. Odorants emitted from anaerobically digested biosolids. Sources recording only TVOSC or MT and DMS are not included.

Ambient conditions / near dewatering or storage	Dewatered biosolids: Short term storage, < 30 days	Dewatered biosolids: Long term storage, > 30 days	Land application
sulfur dioxide [1] dimethyl sulfide [2] dimethyl disulfide [1,2] dimethyl trisulfide[1,2] p-xylene[1,2] toluene[1,2] benzene [2] trimethyl benzene[1] dimethyl benzene[1] acetic acid [1] 2- butanone [1,2] 2- butoxy-ethanol [1] 2-ethyl-hexanol [1] a-pinene [1,2] carene [2] limonene [2] dodecane [2] diethyl ether [2] octane[1] decanal[1] hexanal [2] heptanal [2] limonene[1] nonanal[1] octamethyl - cyclotetrasiloxane[1] benzaldehyde[1]	hydrogen sulfide *[4] methyl mercaptan *[4] dimethyl sulfide *[3, 4] dimethyl disulfide* [3, 4] dimethyl trisulfide * carbonyl sulfide[4] ethyl mercaptan [4] carbon disulfide [3, 4] thiophene [4] isobutyl mercaptan [4] 2-butanone [3] acetone [3] ammonia [3] trimethylamine [3, 4] dimethyl amine [4] isobutylamine [4]	methyl mercaptan [5, 6] hydrogen sulfide [5] dimethyl sulfide [5, 6, 7] dimethyl disulfide [7] dimethyl trisulfide [7] indole [5, 6, 7] skatole [5, 6, 7] p-cresol [5, 6] ethyl benzene [6] toluene [6] long chain aliphatic hydrocarbons [7] terpenes [7] alkyl benzene [7] other aromatics [7]	ammonia [8] trimethylamine [8] dimethyl disulfide [8, 9] dimethyl sulfide [8, 9] carbon disulfide [8] toluene [9] ethyl benzene [9] xylene [9] acetone [8] 2-butanone [8] Ŭ-pinene [9] ƀ ï pinene [9] p-cymene [9] limonene [9] c9 ï c17 [9]

* Compounds were detected in the WERF study (Adams, 2004) and subsequent papers.
1 Zarra et al. (2009) took ambient air samples near sludge dewatering centrifuges and analysed using GC-MS/FID
2 Lehtinen and Veijanen (2011) analysed ambient dewatering emissions with GC-PID and GC-MS
3. Rosenfeld et al. (2001b) sampled dewatered biosolids using flux chambers and analysed chamber headspace using adsorption tubes and TD-GC-MS and Draeger tubes for ammonia from headspace
4. Easter et al. (2009) measured emissions from dewatered stored biosolids using a flux hood and analysed using GC-FPD for VOSCs and adsorption tubes with GC-MS for amines
5. Muller et al. (2014) analysed large scale piles during storage using an equilibrium headspace system and analysed using GC-MS with appropriate columns
6. Chen et al. (2004)analysed dewatered biosolids long term storage using static headspace sampling method and analysed using GC-FID for VOSCs and GC-MS for aromatics
7. Gruchlik et al. (2012)and Gruchlik et al. (2013) measured headspace compounds using SPME with GC-MS, *compounds shown in italics were not confirmed with standards*
8. Rosenfeld et al. (2001a) sampled land applied biosolids using flux chambers and analysed using GC/MS with suitable columns, ammonia measured using Draeger tubes
9. Laor et al. (2011) sampled land applied biosolids emissions using short term (1hr) headspace incubation then analysed using HS-SPME-GCï MS

Table 19. Formation and degradation pathways for odorants typically detected in anaerobically stabilised biosolids

Compound group	Conditions of formation
Volatile organic sulfur compounds: MT, DMS, Dimethyl disulphide (DMDS)	Degradation of methionine and cysteine in anaerobic conditions, methylation and dimerization of MT 1
H2S	Degradation of cysteine and reduction of sulfate in anaerobic conditions 1
Organic Volatile aromatic compounds: Indole, skatole	Degradation of tryptophan 2
p-cresol (+ butyric acid)	Degradation of tyrosine 2, 3
Volatile fatty acids, ketones, aldehydes	Partial digestion of the organic material 4
1. Gostelow et al. (2001), 2. Chen et al. (2004), 3. Novak et al. (2012), 4. Suffet et al. (2009).	

While a range of compounds have been measured in emissions from biosolids, the volatile sulfur compounds are still considered the main odorants due to their high concentrations and low odour thresholds, unpleasant characters and negative hedonic tones (Turkmen et al., 2004, Devai and DeLaune, 1999, Adams, 2003, Ras et al., 2008). However, VOCs such as p-cresol, Ŭ-pinene, indole and skatole have been measured in emissions from anaerobically stabilised biosolids at levels thought perceivable by humans (Chen et al., 2007, Higgins et al., 2003).

The generation and degradation of VSCǒs has been studied by Lomans et al. (2002) in freshwater sediment and this was applied by Higgins et al. (2003) to examine the generation pathways in anaerobically stabilised biosolids storage. A summary of the agreed odour generation mechanisms in anaerobically digested biosolids cakes is presented in Figure 10. These pathways were determined by upsetting the system with inhibitors or stimulants and monitoring the evolved gasses in the systems headspace by Higgins et al (2002b, 2003, 2006, 2008), the findings were largely supported by other authors (Samaras et al., 2013, Novak and Park, 2010, Tepe et al., 2008, Verma et al., 2006, Kim et al., 2005a).

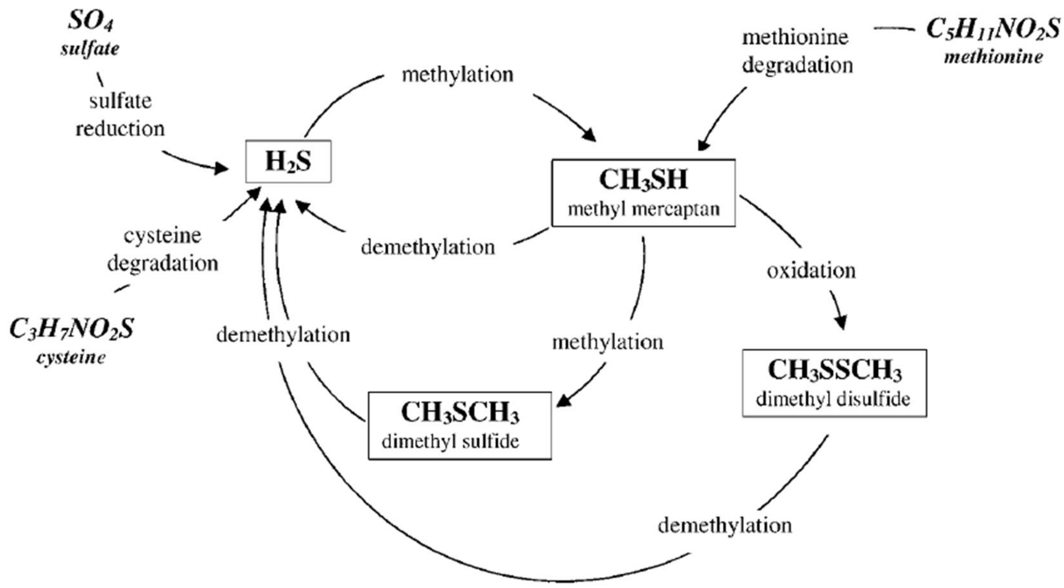

Figure 10. Cyclic pathway of volatile sulfur compound transformation during biosolids storage (Higgins et al., 2006). Note key *substrates* for odour production in bold italics and key odour causing compounds outlined in boxes

The relationship between VSCs (MT, DMS and DMDS), emitted as the cake is stored, is typical of the pathways shown in Figure 10. The headspace emission profile as incubated biosolids cakes are stored is shown in Figure 11. DMDS is emitted due to the dimerization of the MT with the remaining oxygen in the system, the peak decreases as the methanogenic activity increases (degrading the DMDS and MT) and the oxygen in the system is depleted. The MT peak occurs after the DMDS one, and it decreases as it is methylated by microbes to form DMS. All peaks reduce as the methanogenic population increases so that at steady state the generation rates are equal to the degradation rates. Therefore it's expected that factors that prevent or prolong the system reaching steady state (e.g. antibiotics, salinity, oxygen etc.) may increase the potential for odour generation (Turkmen et al., 2004).

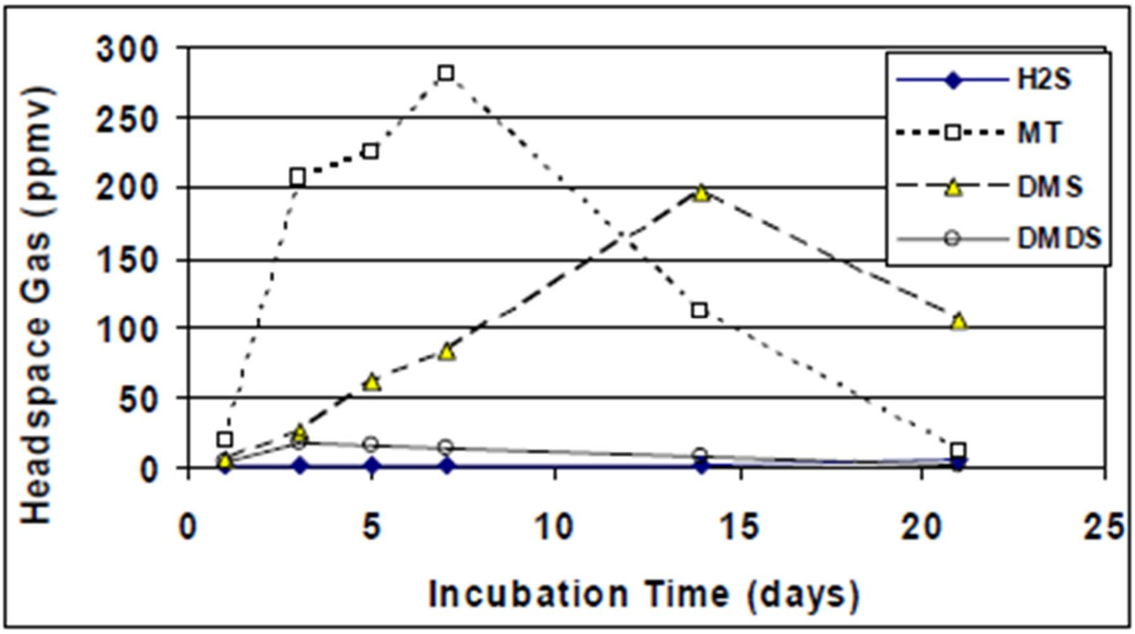

Figure 11. Typical emission profile of MT, DMS and DMDS in the headspace of aged anaerobically digested biosolids (Adams et al., 2007)

Organic volatile aromatic compounds were seen in the headspace of incubated biosolids after the VOSCs have disappeared from about day 30. This delay may be due to substrate competition (Chen et al., 2004), the slow degradation of odour precursors (seen in Table 19) or the gradual conversion of compounds over time (Kacker et al., 2011). The concentrations of organic aromatic compounds are much lower than the volatile sulfur compounds initially emitted by around two orders of magnitude. Yet due to the low odour thresholds of these compounds, they may still contribute to the biosolids odour, as suggested by the high odour concentrations in the headspace of biosolids at extended storage times (day 100) (Johnston et al., 2009).

Laor et al. (2011) noted differences in the compounds emitted from three different anaerobically digested sludge samples. The main differences were of S-containing compounds (CS_2, DMDS, and DMTS), BTEXs, and p-cymene and alkanes. These differences may be attributed to different wastewater sources or treatment processes in the plants. Common compounds BTEXs, terpenes and alkanes were suggested to be useful as chemical fingerprints of odours from wastewater treatment plants, depending on industrial, domestic and run off in the catchments.

1.2.2. Process implications

As the majority of the odorants detected (Table 18) are generated from the degradation of organic matter (Table 19), the performance of the anaerobic digesters are directly linked to the potential for odour emissions from the biosolids. The performance of the anaerobic digesters is commonly assessed by solids retention time (SRT), volatile solids reduction (VSR), as well as the remaining volatilise solids through bio-methane potential (BMP) test. As shown in Table 20, longer solids retention times generally result in lower odour emissions. This trend is evident at individual sites, as differences in efficiency, feeds and dewatering and conveying downstream complicate the effect when different sites are compared.

No correlation between VSR and odour emissions from the biosolids product was noted (Adams, 2004, Muller et al., 2007b). It's thought that VSR, which measures the bulk reduction in volatile solids, more accurately represents the degradation of the readily biodegradable organic matter, rather than the more recalcitrant proteins (Muller et al., 2007b). The remaining protein content, after digestion, has been suggested as an indicator for the potential production of odours (Adams, 2004). Proteins in biosolids may be bound by cation complexes, but freed by shear forces. Loosely bound proteins are more likely to be biodegraded, resulting in odour formation. Shearing frees tightly bound proteins, while complexes bind them. Anaerobic digestion as well as dewatering and chemical dosing affects protein partitioning. Other factors such as the digester shape and layout appear to influence odour emissions (Table 20). It's likely that the different designs or sites display diverse operational efficiencies affecting odour emissions.

1.2.2.1. Temperature

Anaerobic digesters can be run at either mesophilic or thermophilic conditions; the difference in temperature is likely to affect the volatilisation and formation of odorants, degradation kinetics and microbial community composition.

Thermophilic digesters appear to produce more offensive biogas and digested sludge compared to mesophilic digesters (Table 20). However, after dewatering the biosolids emissions improve and are near neutral. This has been attributed to the greater presence of volatile fatty acids which are removed in the centrate during dewatering (Shao et al., 2002) or the greater removal of soluble proteins (Higgins et al., 2004).

Biosolids produced from thermophilic digestion also have a lower headspace TVOSC peak, which occurs at a later storage time (Table 20). The lower emissions are potentially linked to the greater degradation of odour precursors at the higher temperature. While, the different temporal patterns in the stored biosolids emissions are attributed to the inhibition of both TVOSC producing microbes and methanogens due to the reduction in temperature during dewatering and storage. Another reason for the lag time before the TVOSC peak for thermophilically stabilised cake may be product inhibition due to the higher VFA content after thermophilic digestion, reducing the protein degradation rate (Wilson et al., 2009).

1.2.2.2. Multi-stage digesters

The addition of more digestion stages offers more control over the digestion process as different vessels can be optimised to favour different degradation stages and the stages can buffer the flows through the system. Table 20 shows examples of how multistage digestion has improved odour emissions of produced biosolids. Recently some authors have suggested that different portions of the biosolids can only be digested in aerobic or anaerobic conditions (Kumar et al., 2006a, Park et al., 2006). While Novak et al. (2003) suggested that different types of biopolymers are released after aerobic and anaerobic digestion. Extracellular polysaccharides are predominant after aerobic digestion, while proteins are more common after anaerobic digestion. Therefore, aerobic conditions in the final digestion stage will reduce the proteins levels remaining in the biosolids. However, the residual extracellular polysaccharides may affect polymer requirements during dewatering.

1.2.2.3. Sludge origin

While anaerobic digestion of sludge may be perceived as a ðbreakô in odor connectivity between upstream processes and the biosolids produced (Murthy et al., 2004), the composition of sludge entering the digester can affect digester operation and therefore downstream processes.

Different proportions of cation associated organic matter, proteins, and soluble sulfur containing compounds are found in primary sludge and WAS (Table 20). These differences, appear to affect odours from the final biosolids product. WAS has more cation associated organic matter and high molecular weight soluble proteins which are not thought to be fully degraded in the anaerobic digesters (Wilson and Novak, 2009, Aldin et al., 2011).

Table 20. Review of literature relating to anaerobic digester operation and odour emissions from the produced biosolids.

Variable	Literature examples
Solids retention time (SRT)	Comparing the SRT in the digesters at different sites didn't provide a significant positive correlation with lower biosolids odour emissions (Adams, 2004). Adams et al. (2007) showed that increasing the SRT from 15 to 30 days only reduced the peak TVOSC emissions by 30%. Verma et al. (2006) showed a 50% reduction in total sulfur emissions from stored biosolids by increasing the SRT to 40days from 15days. Introducing recuperative thickening, thereby increasing SRT, reduced odour emissions from the headspace of stored biosolids cake in terms of both olfactometry and TVOSC levels (Davis, 2012).
Volatile Solids Reduction (VSR)	No correlation between VSR% and odour emissions from the biosolids product was noted (Adams, 2004, Muller et al., 2007b, Toffey and Higgins, 2007).
Digester shape	Egg shaped digester produced less TVOSCs in headspace than the 'pancake shaped' digester, acid gas had a delayed, but higher TVOSC peak, however the relative retention times were not stated (Adams et al., 2007).
Multi stage digestion	The addition of an aerobic stage following anaerobic digestion was seen to reduce the peak TVOSC headspace concentrations from the dewatered cake for both thermophilically and mesophillically anaerobically digested sludge (Kumar et al., 2006a). Park et al. (2006) showed a reduction in labile protein in the biosolids using sequential anaerobic - aerobic digesters. Addition of aerobic digestion after thermophilic digestion was noted by Wilson et al. (2009) to increase peak VOSCs emissions, compared to a single thermophilic reactor. This increase was suggested to be due to the inhibition of methanogens involved in the degradation of VOSCs due to the presence of oxygen. Combinations of mesophilic and thermophilic digestion showed lower biosolids TVOSC emissions compared to only mesophilic stages (Adams et al., 2007). However, the improvements could also be attributed to improved mixing or the increased residence time.
Thermophlic vs mesophilic	Thermophilic digesters have been noted to have greater H_2S, NH_3 and TVOSC emissions (Wu and Parker, 2004, Kumar et al., 2006a), likely due to the increased volatilisation at the higher temperatures compared to mesophilic digesters (Du and Parker, 2013). Shao et al. (2002) measured the strength (olfactometry), intensity and hedonic tone of the digested and dewatered sludge when changing a digester from mesophilic to thermophilic. The thermophilically digested sludge had a more offensive hedonic tone compared to the mesophillically digested and dewatered sludge, however when the former was dewatered its hedonic tone was near neutral. Thermophilically digested biosolids produce lower peak TVOSC when stored. The peaks occur much later, however can take much longer to dissipate compared to mesophillically digested biosolids (Murthy et al., 2009, Wilson et al., 2006, Adams, 2004, Kumar et al., 2006b, Novak et al., 2012). Thermophilically digested biosolids produce lower peak TVOSC concentrations the ratio of MT to DMS is higher (Wilson et al., 2006). Lower TVOSC concentrations were seen in the headspace of cakes from multistage digesters, where the temperature was sequentially reduced 55°C to 37°C compared to cake from a single stage digester at 55°C (Kim and Novak, 2011) Temperature- phased digestion uses two digesters, the first thermophilic and the either mesophilic or slightly higher, produced biosolids where the peak emission occurred between those of mesophilic and thermophilic, and with lower peak concentrations (Murthy et al., 2004).
Sludge origin (WAS to PS ratio)	Temporal variation in upstream solids characteristics were attributed as the cause for variation in the headspace VSC profile for biosolids taken from the same plant, months apart with no noticeable difference in digester operation (Murthy et al., 2003a). Aldin et al. (2011) compared the digestion of primary and WAS and observed that primary sludge showed higher degradation efficiencies

Variable	Literature examples
	for VFAs and bound proteins compared to WAS. However the differences were only small as the primary sludge had initially lower levels of protein compared to the WAS Du and Parker (2013) identified a greater proportion of soluble sulfur containing compounds in digested biosolids, particularly WAS. Sludges differ in their levels of cation associated organic matter, which is typically greater in WAS. Muller et al. (2007b) posits shearing during dewatering could release the organic matter associating with iron leading to greater peak VOSC emissions. A negative correlation between dewatered sludge headspace sulfur concentrations and % of WAS in digester feed was identified by Adams (2004), however an outlier was a site with predominant WAS feed which also had high headspace concentrations. Therefore itôs suggested that other confounding parameters are present as there were many differences between the sites such as different solid retention times and dewatering practices.
Pre-treatment	The Cambi process which uses the release of pressurised steam to hydrolyse organic matter prior to digestion has been applied to a number of full scale plants due to its improvements in biogas and reductions in solids. Itôs odour implications have been evaluated in both lab scale (Wilson et al., 2009, Wilson et al., 2011, Dhar et al., 2011b, Murthy et al., 2009) and full scale plants (Murthy et al., 2009, Higgins et al., 2011, Evans, 2003). The pre-treatment generally provides a reduction in peak TVOSC emissions from the dewatered cake; however the degree of improvement varied between lab and plant trials, likely due to the different sludge properties and digestion efficiencies. MicroSludge® uses a combination of mechanical and chemical processes, using high pressure and alkaline addition. It achieved a 50% reduction in peak TVOSC in the headspace of dewatered sludge, however the controls showed a rather high peak TVOSC to begin with (Adams et al., 2007). Ultrasonic pre-treatment was investigated in laboratory studies, while reductions in peak TVOSC were seen relative to the control digester, the results varied between runs (Muller et al., 2005, Muller et al., 2009). Aldin et al. (2009) showed that ultra sonication pre-treatment, didnôt significantly reduce bound proteins levels, however the odour implications were not tested. Enhanced enzymic hydrolysis showed generally lower biosolids odorant emissions compared to conventional mesophilic anaerobic digestion(Murthy et al., 2009). Other chemical treatments, such as the dosing of hydrogen peroxide and iron with and without mechanical pre-treatment (High pressure), showed lower H_2S and MT levels in the digested sludge and biogas (Dhar et al., 2011a, Dhar et al., 2011b). However, itôs not known what effect this would have on the emissions from the final biosolids product. Lab scale trials which sheared a recycle stream of digested sludge using a laboratory mill saw a reduction in protein levels (Muller et al., 2007a) and a reduction in TVOSC levels in the headspace of the dewatered cake (Basu et al., 2004).

In theory greater proportions of WAS entering digesters lead to more proteins remaining in the biosolids potentially leading to odour emissions. This hasn't specifically been supported experimentally (Table 20). The increased rate of mineralisation of sulfur compounds from primary sludge also supports the theory that lower odours are emitted from biosolids produced from digested primary sludge (Wilson and Novak, 2009).

1.2.2.4. Pre-digestion processes

As the hydrolysis of organic material is the rate limiting step in anaerobic digestion, pre-digestion methods have been developed to aid hydrolysis, thereby improving digester performance. Many different approaches have been trialled in recent years, as outlined by Carrère et al. (2010); however the odour implications are rarely investigated. The increased digestibility of sludge following pre-digestion processes is thought to reduce odour emission as the degradation of odour precursors is increased (Dhar et al., 2011a, Dhar et al., 2011b). Another suggestion is that lower odour emissions are associated with the reduction in the degradation of proteinaceous material in the cake due to product inhibition, because of the greater residual VFA levels (Wilson et al., 2011).

Reviewing the literature for odour emissions relating to pre-treatment is shown in Table 20. Pre-treatment processes such as Cambi and Microsludge showed improved biosolids headspace odour emissions. Treatment methods using mechanical pre-treatment, enhanced enzymic hydrolysis and chemical dosing also provided reduction in odour emissions. Improvements in odour emissions due to ultrasonic pre-treatment weren't clear.

1.2.2.5. Dewatering of biosolids

The shear force exerted on biosolids as they are dewatered, releases bound organic matter, making them bioavailable and producing volatile sulfur compounds when degraded (Muller et al., 2004, Murthy et al., 2002). The effect was anecdotally observed in numerous sites as odour emissions increased following the incorporation of high speed centrifuges to improve TS concentration in the dewatered cake (Mendenhall et al., 2003, Ross et al., 2002). High speed centrifuges have been strongly linked to higher levels of TVOSCs in the headspace of dewatered biosolids (Higgins et al., 2002a, Erdal et al., 2008, Higgins et al., 2007, Murthy et al., 2003a, Muller et al., 2004, Gruchlik et al., 2012). Shear forces, also exerted during prolonged conveying or handling, have also been associated with increased TVOSCs, ammonia and amines and odour intensity in the stored sludge headspace as well as a worsening of hedonic tone (Adams, 2004, Mendenhall et al., 2003) (Higgins et al., 2002b).

Table 21 details the literature findings on how odour emissions from anaerobically stabilised biosolids are affected by the dewatering process. The shearing in different dewatering methods affects the resultant biosolids emissions. High speed centrifuges have greater shear, and therefore emissions compared to medium or low speed centrifuges. While belt filter presses, even when producing similar TS wt% to centrifugally dewatered biosolids produce biosolids with much lower odour potential (Table 21).

Dewatering has been suggested to inhibit methanogen activity in the resulting cake, due to exposure to oxygen or reduced moisture levels (Chen et al., 2005, Kumar et al., 2006b, Verma et al., 2006). The TSwt% of the cake, as well as the shear during dewatering, has been proposed to affect the headspace TVOSCs, with less emissions from lower TSwt% cakes (Higgins et al., 2002a, Adams et al., 2007, Verma et al., 2006). Lomans et al. (2001) suggested that the methanogens are inhibited due to the cake dryness.

High shear dewatering has also been associated with “Sudden Increase” (SI) in the amounts of pathogenic strains of microorganisms, from the stabilised sludge. Chen et al. (2011) associated the increased microbial activity due to shear and oxygen availability during dewatering resulted both in SI and increased odour production. Other reasons for SI that have been put forward are the reactivation of non-culturable pathogens due to high levels of substrate made available after shearing, as the effect is less evident using low shear equipment such as belt filter presses (Adams et al., 2007, Murthy et al., 2003a).

Centrifugal dewatering parameters can be interrelated, making it difficult to isolate any specific parameter affecting odour emissions, while retaining acceptable cake TSwt%. The shear force during centrifugal dewatering is contributed to by a range of parameters, including bowl speed, torque, scroll speed and weir height (Higgins et al., 2005). Settings which favour lower odour emissions are lower speeds and torques which exert less shear force and also require lower polymer doses (Table 21)

Increasing polymer dosages have been widely shown to increase biosolids emissions of reduced sulfur compounds, odour intensity, detection and recognition thresholds and result in worsening hedonic tone (Murthy et al., 2002, Higgins et al., 2002b, Higgins et al., 2005). As polymer doses are increased less polysaccharide and proteins are removed in the centrate, instead they appear to be bound to the dewatered cake (Higgins et al., 2005). Indeed, some polymers have been known to degrade in the dewatered biosolids and form trimethyl amine (TMA), a fishy smelling amine (Subramanian, 2004) (Table 21). Rosenfeld et al. (2001b) looked at different cationic polymers used in the dewatering of anaerobically digested biosolids using a plate and frame system. The study found that while variations were seen between odorant concentrations, the olfactometry analysis showed no significant variation between the treatments.

Table 21. Compilation of findings from the literature regarding how dewatering affects odour emissions from anaerobically stabilised biosolids

Dewatering method	Adams et al. (2007) showed that using different types of centrifuges influence odour emissions. Medium speed centrifuges achieved the same TSwt% as a high speed centrifuge however produced less TVSOC, suggesting solids content is not the only factor. When rotary presses or belt filter presses (BFPs) were compared to centrifuges, the TSwt% as well as the emissions of the centrifuged samples were typically higher Murthy et al. (2003a) showed that when the same biosolids were dewatered using high solids, low solids centrifuge and BFP to a similar TSwt%, the processes exerting more shear force emitted more MT and DMS. Shearing of digested sludge prior to dewatering using BFPs did produce low levels of DMS in headspace where there were none before, further enforcing the role of shear as the variable between these processes Even when BFP dewatered sludge was double pressed to similar TSwt%, emissions were still lower than those of centrifuged samples (Adams et al., 2007).
Centrifuge parameters	The feed-rate through the centrifuges was noted by Adams et al. (2007) to also affect the TVOSC emitted from the cake, the faster the rate, the less shear, and therefore lower the emissions. Varying the differential rpm in high speed centrifuges changed the strength of emissions in the headspace for similar profiles (Murthy et al., 2003a). The main location in the centrifuge that the shear is thought to occur is as the cake is extruded through the weir disk, as identified from the headspace TVOSCs taken from various locations throughout the centrifuge itself (Higgins et al., 2005). Increasing the centrifuge torque was correlated with increases in the dilution threshold and the TVOSC concentration of the headspace emissions. Higher torque as well as increasing shear, require an increased polymer dose which can reduce the removal of soluble proteins in the centrate (Higgins et al., 2005). The same effect on the dilution thresholds and TVOSC concentration and optimum polymer dose was also seen when the polymer addition point was moved upstream, likely due to the increased shearing of the conditioned cake as it travels greater distances. The study by Higgins et al. (2005) noted that the plant at which the study was conducted, decreased the centrifuge torque, and subsequent polymer dosing, resulting in less odorous cake. Adams et al. (2007) showed in a number of plant trials that higher torques were correlated with higher emissions of TVOSC, but less methane suggesting methanogen inhibition.
Polymer dosage	Subramanian (2004) showed that the abiotic degradation of certain polymers is too slow to detect, however the biotic breakdown to TMA was shown in the lab. Such emissions increased after shearing, likely due to the breakage of polymer linkages.

1.2.2.6. Chemical amendments

Iron salts are commonly used for the control of hydrogen sulfide emissions in the sewer network, secondary treatment, or the anaerobic digester. Novak (2010) identified that where the iron salts were added to the wastewater affected the downstream odour generation. Table 22 shows studies of cation (Fe, Al) dosing and the odour response throughout biosolids processing.

The cations can form organic complexes binding extracellular proteins, making them less readily degradable. However, the reduction of iron under anaerobic conditions may reduce the binding strength of these complexes. Adams et al. (2007) noted that a 40% reduction in iron associated protein occurred over a 40 day SRT, in agreement with the findings of Park et al. (2006), that iron associated proteins can be degraded in anaerobic conditions. However, as higher biosolids emissions result when iron salts are added to the digester feed, itôs likely that the iron complexes reduce the overall degradation of proteins in anaerobic digesters, even though some of the complexes are dissociated. These complexes can then be dissociated by shear during dewatering, releasing this undegraded organic matter. Aluminium organic complexes are more stable than those containing iron, so they are less likely to be digested or released under shear conditions (Novak, 2010). Alum addition to the biosolids during dewatering consistently appeared to reduce headspace emissions, but also resulted in increased optimum polymer dosing (Table 22).

The effect of cation dosing appears to depend on dosage size, location, shear and judging by the variable response in full scale trials other factors that havenôt yet been identified (Table 22). It is suggested that insufficient iron salt dosing may inhibit methanogens but not sequester the proteins leading to greater emissions (Higgins et al. 2002b). Therefore the effect of cation dosing on methanogens should be established.

1.2.2.7. Other chemical amendments

In addition to cation dosing, other chemical amendments, marketed to reduce emissions from wastewater solids processing, were present in the literature. The modes of action of the treatments and their demonstrated effectiveness from the reviewed literature are presented in Table 23. The majority of the studies reviewed the concentrations of biosolids headspace emissions, while others also included sensorial evaluation.

Adams et al. (2007) tested a range of products marketed to reduce odours, however upon testing; using the recommended dosages, none of the additives appeared to significantly reduce the TVOSC levels in the dewatered sludge headspace. Johnston et al. (2009) compared different additives for odour control using olfactometry analysis. Suitable additives varied in how long they could control the odour, being suitable for either short or long term control. However none of the additives could reduce the olfactometry dilution thresholds below 10^5, signalling more studies, specifically field trials, are needed for odour improvement. Other trials were conducted, while some saw favourable results (Table 23), full scale trials are needed at sites before implementation.

1.2.2.8. Storage and land application

The typical temporal profile of VOSCs emitted in the headspace of biosolids samples as they are aged has been well described in many studies (Figure 11). The interplay between VOSC producers and the degraders (methanogens) are responsible for this pattern (Higgins et al., 2006). The magnitude and the timing of the peak are known to be affected by factors such as thermophilic temperature shock, iron addition, shearing, VFA levels, and chemical amendments. Temporal patterns of other odorant generation has also been investigated by Chen et al. (2004) with volatile aromatic compounds dominating emissions at ages greater than 30days.

The adverse effects of shearing on biosolids odour emissions, arenôt suggested to be long term as odours emitted from the land application of biosolids dewatered belt filter presses were initially lower but after two weeks were the same as for centrifugally dewatered biosolids (Rosenfeld et al., 2001a). However, the differences in emissions in the first two weeks may be significant. ôSeedingô freshly dewatered cake with stored cake was investigated by Williams et al. (2008). Fewer emissions were seen in the seeded cake, with 91% reduction in headspace TVOCs seen when 10% aged cake was incorporated, however full scale analysis is required to determine the benefit. The reduction of H_2S emissions when more stored sludge was added may be associated with the higher pH of the stored cake.

Table 22. Compilation of reviewed literature concerning the dosing of cations (Fe and Al) in biosolids processing and odour response

Addition Location	Effect of cation dosing
Activated sludge and Digesters	Addition of the cations to the activated sludge, perhaps to reduce soluble phosphorus, was seem to reduce cake odour emissions (MT, TVOSC) for varying degree for sludge from 7 different plants (Novak and Park, 2010). Addition of iron to the anaerobic digesters, reduced the requirements for polymer during dewatering improving the cake TSwt%, however dramatically reduced the levels of TVOSC emitted from the cake (Higgins et al., 2002b, Novak, 2010). Kim and Novak (2011) noted that iron salt addition to the digester shortened the time it took for TVOSC emissions to peak for thermophilic digested biosolids. Increased peak TVOSC emissions when iron salts are added to the feed were seen by Adams et al. (2007) Higher ratios of iron/aluminium lead to more available VS for destruction after shearing (Muller et al., 2007b).
Dewatering	Higgins (2010) noted addition of metal salts during dewatering or to the cake reduced headspace TVOSC production. The addition of a range of aluminium and iron salts to the cake produced favourable odour reduction, despite different levels of effectiveness (Novak, 2010). Increasing iron chloride doses decreased MT and DMS emissions and hedonic tone, but increased the time for the emissions to peak. Likely due to the sequestering and slow release of proteins from iron complexes(Higgins et al., 2002b). Other sites (lab and full scale) didn't achieve the same degree of odour reduction for the cation dosing, suggesting a range of interactions are involved (Gruchlik et al., 2012) (Higgins, 2010). Increasing alum doses reduced emissions but increased optimum polymer dosing requirements (Adams et al., 2007, Kim et al., 2011b) Higgins (2010) suggests that the dose of cations required to reduce TVOSC peak emissions is influenced by the amount of shear imparted on the biosolids and dosing location. When H_2S emissions are present the addition of alum would promote its release, while iron would lower emissions (Higgins, 2010) Iron addition to the biosolids for one plant during dewatering showed favourable reductions in DT, RT, DMS and intensity, yet didn't affect DMDS. The opposite of this effect was seen in another plant that was tested (Higgins et al. 2002b). These findings may be related to the slight increase (16%) in the levels of iron in the biosolids, which acts to retain some protein, however not enough to sequester sulfur in the biosolids yet it inhibits VOCS producers, resulting all up in more emissions. Uneconomical (>10 dry wt%) doses of iron chloride were needed for control of headspace emissions (Toffey and Higgins, 2006) Alum dosing in a full scale plant had a more varied effect, compared to lab scale. One site showed improvements, another displayed the opposite (Chen et al. 2007). The effect of alum dosing on the methanogen populations is not clearly elucidated and may be related to the observed differences.

Table 23. Compilation of the reviewed literature evaluating chemical amendments mode of action and effectiveness in controlling biosolids odour emissions

Additive	Mode of action	Location	Findings
$FeCl_3$	Bind sulfide, mercaptans and proteins, enhance degradation	Before dewatering	Addition prior to polymer addition reduced headspace VOSCs and odour (Higgins et al., 2002b) Addition showed good reduction in emissions < 10 days of storage, (Johnston et al., 2009) Greatest reduction in NH_3 and amine compared to hypochlorite and lime (Mendenhall et al., 2003)
Lime	microbial suppression	before dewatering	Low level dosing < pH 11 has better CFU control however may release more MT and DMS compared to control (Erdal et al., 2004) Lime dose needs to inhibit both protein degraders and methanogens (Adams et al., 2007). Lime addition, while reducing the VSC emissions, produced a fishy odour, and thought to be associated with Trimethyl amine(Higgins et al., 2002b)
		after dewatering	Addition of calcium hydroxide decreased sulfur emissions but produced TMA in headspace(Higgins et al., 2002b)
Ferric sulfate	reduce protein bioavailability and enhance degradation	after dewatering	Large reduction in headspace emissions (~75% reduction) for <10 days storage(Johnston et al., 2009)
Calcium nitrate	electron acceptor, promotes degradation in anoxic conditions	before and after dewatering	Better reduction (96% for H2S and 93% for VSC's) over storage of 3 days when applied after dewatering, still some improvements relative to control when applied to liquid sludge before. (Weissenberger et al., 2006)
calcium nitrate with anthra - quinone	promotes anoxic vs anaerobic conditions	after dewatering	Greater doses reduced MT and DMS headspace emissions and after dewatering improved hedonic tone (Higgins et al., 2002b)
potassium nitrate	promotes anoxic vs anaerobic conditions	after dewatering	Higgins et al. (2002b) showed that high levels of potassium nitrate prior to dewatering reduced the MT concentration; however this was associated with an increase in DMDS
Alum	reduce protein bioavailability and enhance degradation	after dewatering	Large reduction in headspace emissions (~85% reduction) for <10 days storage(Johnston et al., 2009)
ash, lime kiln dust	inhibit microbial activity, reduce protein bioavailability	after dewatering	Rosenfeld (2001) mixed high Carbon ash to biosolids before land application and noted that a higher ash ratio decreased emissions of DMS, CS2, NH3, TMA, acetone and Odour units over supplication time. Addition showed good reduction in emissions < 10 days of storage, (Johnston et al., 2009) Toffey and Higgins (2006) found ash from different sources had different effectiveness in controlling emissions.

Additive	Mode of action	Location	Findings
Activated carbon	adsorption or oxidation	after dewatering	Large reduction in headspace emissions (~80% reduction) for <10 days storage (Johnston et al., 2009)
Bio augment	stimulate methanogen activity	into digesters	reduced headspace emissions of DMS and MT (Tepe et al., 2008) Proprietary nutrient blends reduced peak TVOSC emissions by a third when added before digestion and 70% when added before dewatering (Toffey and Higgins, 2006).
		Dewatering	Bio-Organic catalyst addition only was effective when added to centrifuge, rather than sprayed on dewatered biosolids surface (Toffey and Higgins, 2006) .
Cyclodextrin	adsorption or oxidation	after dewatering	No effect relative to control for <10days (Johnston et al., 2009)
H_2O_2	Oxidation	after dewatering	Reduction in headspace emissions not significant for <10days storage(Johnston et al., 2009)
$KMnO_4$	Oxidation	after dewatering	Reduction in headspace emissions not significant for <10days storage(Johnston et al., 2009)
calcium hypochlorite	Oxidiser	after dewatering	Reduced MT, DMS and DMDS in headspace (Higgins et al., 2002b)
PECO Mag sulfite	reduce protein bioavailability, enhance degradation	after dewatering	Increased emissions for storage <10days (Johnston et al., 2009)
Epsom salt	reduce protein bioavailability and enhance degradation	after dewatering	Reduction in headspace emissions not significant for <10days storage (Johnston et al., 2009)
Humic mineral product		Onto dewatered cake	Slight reduction in headspace TVOSC, compared to control after application (Toffey and Higgins, 2006)

The results of headspace emission profiles for ageing biosolids suggest that transport and land application should be conducted after the initial headspace TVOSC peak has occurred. However Murthy et al. (2002) showed an increase in detection threshold and recognition threshold when anaerobically digested biosolids were stored for up to 60 days prior to land application. The exact storage conditions and analysis method for these findings weren't defined. While, Brandt et al. (2009) showed that the application of anaerobically stabilized biosolids stockpiled for about 50 days resulted in a higher odour intensity compared to shorter stockpiling times. Higher levels of p-cresol and VOSCs were noted in the headspace of biosolids cured for shorter periods of time. However the olfactometry results also didn't show any significant difference in the odour concentrations for the different biosolids samples. The authors concluded that they could not confirm the benefit to short term vs long term biosolids stockpiling before spreading.

In contrast, it was found that curing of biosolids prior to application for at least a week improved the odour intensity, concentration and hedonic tone (Muller et al., 2014), however the solids stockpiled were from anaerobic digesters with long solids residence times > 30 days, so this trend may not be consistent with other sources. Long-term stockpiling of biosolids for more than 6 months produces low odour product (Novak et al., 2012) These findings suggest that the headspace method may not accurately represent odorous emissions from the biosolids when applied to land.

1.3. Aerobic digestion

Only six resources were reviewed for this stabilisation method. Two early papers by Koers and Mavinic (1977) and Eikum and Paulsrud (1977) used an odour panel and the odour intensity index to evaluate parameters affecting and representing the stability of aerobically stabilised biosolids. Carsen and Anderson (2008), Davis (2012) and Rutledge (2014) in conferences presented findings on odour emissions from lab scale and full scale studies of aerobically digested biosolids from a variety of plants in Australia. While Kumar et al. (2006a) evaluated the addition of an aerobic digester following anaerobic digestion to reduce biosolids odour emissions.

The majority of studies appeared to use headspace sampling, incubating sludge samples and then measuring the odorant concentrations in the headspace. Davis (2012) also used flux hood sampling, while the setup of Carsen and Anderson (2008) involved sweeping the surface of biosolids stored in drums with air to generate emissions, being a cross between headspace and fluxhood sampling. The odorant analysis of the reviewed papers was poor, with half measuring only hydrogen sulfide and organic sulfur compounds reporting them as TVOSC and the other using sensorial methods of odour concentration and odour intensity.

1.3.1. Odorants identification

The odour emissions associated with aerobic degradation are generally considered to be quite low as volatile organics are typically broken down and oxidised producing an odourless, hummus like stable product (Metcalf and Eddy, 2003). However, earlier plants appeared to be plagued with poor operation or design of the systems, leading to microaerophilic or anaerobic conditions, producing odorous emissions. Such emissions could occur during digestion, or during the storage of the poorly stabilised product where anaerobic conditions developed. Compounds likely to be formed in anaerobic conditions are volatile fatty acids and alcohols alongside reduced sulfur compounds.

During land application Banwart and Bremner (1976) identified that DMS and CS_2 as well as DMDS are the most abundant sulfur emission from biosolids application in aerobic conditions. Emissions from the aerobic stabilisation process itself may occur. High temperature operation, as occurs in Auto-thermal Thermophilic Aerobic Digestion (ATAD) systems, can promote the release of ammonia as well as reduced sulfur compounds such as hydrogen sulfide, carbonyl sulfide, methyl mercaptan, ethyl mercaptan, dimethyl sulfide, dimethyl disulfide. The higher temperatures and pH in ATAD system means that ammonia and other compounds can be stripped from the sludge during operation (WEF, 2012).

1.3.2. Process implications

The Specific Oxygen Uptake Rate or SOUR is a commonly used method for measuring stability of aerobically stabilised biosolids. Koers and Mavinic (1977) conducted a series of labscale incubations at different temperatures. It was noted that when digesting at 5 °C, an extremely long solids retention time (SRT), greater than 80 days, would be needed to produce a product judged acceptable by an odour panel. The study showed that temperature of incubation needs to be taken into account when using SOUR as a measure of sludge stability.

Plants using aerobic digestion or extended aeration were examined by Rutledge (2014). The sites using extended aeration appeared to exhibit higher headspace TVOSC concentrations peaking on the fourth day of incubation. However, one of the four aerobic digestion sites also exhibited high headspace TVOSC concentrations despite a SRT of 30 days. Suggesting factors apart from digester type, SRT and dewatering need to be considered.

1.3.2.1. Auto-thermal Thermophilic Aerobic Digestion (ATAD)

While these processes are typically covered, emissions from the process include ammonia and reduced sulfur compounds such as hydrogen sulfide, carbonyl sulfide, methyl mercaptan, ethyl mercaptan, dimethyl sulfide, dimethyl disulfide. Carboxylic acids e.g. acetic, propionic and butyric acids are also commonly measured in exhaust gas (Kelly and Warren 1997).

Odours are also emitted during dewatering due to the elevated temperatures of the sludge, this can require cooling to reduce the emission rate. Application to land of liquid (ATAD treated) biosolids was reported by City of Sunrise Florida to result in strong odours, as well as high transport costs, using HRT of 10-15 days and VSR of 49%. Another site, Avon-Vail, Colorado has VSR 55-65%, centrifuge dewatering and drying before distribution however persistent and strong odours were again noted (Layden et al., 2007).

Some observational data noted that odours appeared worst at very negative ORP values in ATAD plants (Kelly et al., 1993). Low airflow rates can lead to lower ORP values, however high air flowrates may cool the system due to evaporative latent heat loss. Poor mixing can also cause localised regions of low ORP. Off gas from poorly operated reactors can contain ammonia and small amounts of reduced sulfur compounds as well as aldehydes, ketones and other unidentified volatile compounds.

Layden et al. (2007) conducted a literature review of the operation and design of ATAD plants, including mentions of odour emissions, however one of the findings were that more research is needed into odour emissions from thermophilic processes. The main parameters related to odour generation in ATAD plants are outlined below:

- The aeration rate is important to control as insufficient oxygen can produce micro-aerophilic conditions and the accumulation of VFS in the reactor- leading to odours, while on the other hand if the rate is too high, excess cooling can prevent the temperature reaching optimal conditions
- High temperatures in ATAD designs (>65°C) may lead to oxygen limitation (producing odours), the temperature of the system can be controlled by altering the feed concentration (however if the feed concentration is too high oxygen limitation may occur)
- Inadequate mixing as well as inadequate aeration can contribute to odours, as shown in full scale plant (Kelly et al., 1993)
- Transient anaerobic conditions may occur in the influent feed if stored or held in tanks before digesters, resulting in the emission of compounds related to the anaerobic decompositions such as (H2S, mercaptans, VFAs or amines as well as ammonia)
- The high temperature of the biosolids, means they need to be cooled to reduce odour emissions due to increased volatility of compounds before dewatering

1.3.2.2. Protein degradation

The effect of the use of sequential anaerobic aerobic reactors on the odour properties of the produced biosolids was evaluated by Kumar et al. (2006a). Aerobic digestion following thermophilic anaerobic digesters doesn't appear to affect peak TVOSC headspace production as levels are already low. However, the addition of aerobic digestion following mesophilic anaerobic digestion showed improvements, as did increasing the retention times for both processes. This is likely due to the greater removal of proteins in the aerobic digesters when the proteins are present.

Greater removal of proteins from digested sludge was also accomplished using mesophilic anaerobic digestion after an ATAD system. While not directly measured, it was hypothesised by Murthy et al. (2000) to improve odour emissions form the resulting biosolids as there is less substrate to produce volatile sulfur compounds. The lower protein levels in aerobically treated vs anaerobically treated sludge was also supported by Novak et al. (2003).

Murthy et al. (2000) investigated the contributions of different parameters associated with ATAD and noted the effects on biopolymer concentrations, that they linked to odour potential. The release of biopolymers during digestion was thought to contribute to the increased dewatering polymer requirements and foaming problems typical of ATAD operations. It was also posited that high biopolymer levels could lead to odour emissions. However, the studies did not specifically measure odour emissions from the biosolids product.

1.3.2.3. Dewatering

Different methods of dewatering were noted to affect the odour emitted from aerobically stabilised sludge, similar to anaerobically digested biosolids. Dewatering using high G centrifuges produced biosolids emitted initially about twice the odour unit emission rate as biosolids dewatering using a low G system (Carsen and Anderson, 2008). Headspace sampling of aerobically stabilised biosolids dewatered using low or high G centrifuges showed comparable H_2S emissions, but about twice the level of TVOSC for samples produced using high G (Davis, 2012).

1.4. Composting

Composting facilities have the potential of producing odour due to the aeration process and exposed surfaces which promote the emission and distribution of odours. The composting process relies on the use of microorganisms (fungi in particular) to degrade organics. The associated temperature rise (biological aerobic self-heating at mesophilic or thermophilic temperatures) acts to suppress enteric pathogens thereby stabilising the biosolids. The temperature increase in the piles increases the rate of volatilisation of odorants with low boiling points. Bulking agents such as woodchips are typically added when to the biosolids input as this helps reduce the moisture content as well as aiding air dispersion through the product (Maulini-Duran et al., 2013). Yet certain bulking agents contain odorous compounds, especially terpenes from plant material.

1.4.1. Odorants identification

No single paper consistently characterised composted biosolids emissions using both analytical and sensorial analysis. There have been a variety of studies based only on the olfactometry data, useful in determining levels that could impact the community when combined with dispersion modelling (Rousseille et al., 2009), however can be difficult to identify causes for poor performance. The types of odour descriptors recorded at various stages of biosolids composting correlates with the expected odorant concentrations. For example, the characters of faecal, rancid and rotten, represent the sulfur compounds and volatile fatty acids in the active stages (Table 24).

Table 24. Odour descriptors throughout stages of biosolids composting

First stage (mesophilic)	Thermophilic	Cooling	Final product	Reference
Faecal, rotten fishy, manure	Rancid, rotten vegetables	Earthy and grass odours.	Earthy and musty	(Suffet et al., 2009)
Rotten/decayed fish, rotten/decayed meat, spoiled food, compost, urine, putrid, latrine and sour (sampled after 10 days)		N/A	N/A	(Rosenfeld et al., 2004)

Six papers measured odorants as shown in Table 25, the remaining papers either used only sensorial methods(Suffet et al., 2008, Gutiérrez et al., 2014), monitored single compounds such as ammonia (Pagans et al., 2006a), represented emissions as total VOC mgC/m^3 (Pagans et al., 2006b) or hadn't quantified the MS signal (Baby et al., 2005).

Ammonia was identified as the dominant compound emitted during composting (in terms of mass flowrate) for many studies (Pagans et al., 2006a, Lazarova et al., 2008, Rosenfeld et al., 2004). Lazarova et al. (2008) saw a great deal of variance in ammonia emissions for different facilities suggesting that TKN wasn't the only contributor to its generation. Trimethylamine was seen in the initial stages of biosolids composting (Lazarova et al., 2008, Suffet et al., 2009). Suffet et al. (2009) suggested that the reduction of TMA occurred quickly in composting reactions, as the fishy smell associated with TMA wasn't detected in intermediate process steps using odour profiling methods. Other amine and amide compounds (such as methylamine and acetamide) were only detected sporadically in small quantities (Lazarova et al., 2008, Maulini-Duran et al., 2013).The emission of the more oxidised forms of the volatile sulfur compounds, DMDS, CS_2, DMS and COS were commonly detected during the composting of biosolids (Table 25), as their emission is related to the degradation of sulfur containing organic matter. DMDS is the dominant sulfur compound for all studies identifying sulfur based compounds (Maulini-Duran et al., 2013, Suffet et al., 2009).

The exhaust gas from the composting processes were characterised by high flow rates and normally low pollutant concentrations, containing mainly VOCs (if properly managed)(Pagans et al., 2006b). Smet et al. (1999) in a study on the composting of green waste reported that the emissions of VOCs occurs mostly in the first stage of composting, as the compounds are products of anoxic biodegradation. Maulini-Duran et al. (2013) compared the emissions from raw sludge and anaerobically digested sludge, and the time it takes for the peak in VOC to occur is around four days later for the anaerobically digested sludge. The authors suggested the emission are linked to the presence of anoxic zones in biofilm particles due to the oxygen depletion due to aerobic metabolism (microbial activity) and also the accompanying temperature increase leading to volatilisation. Rosenfeld et al. (2007) suggests that incomplete digestion of the biosolids can lead to VFAs, aldehydes and ketones and alcohols being present in the composting initially and that they are associate with rancid, vinegar and body odour types smells, and sweet solventy odours.

Terpenes are thought to be intermediates aerobic metabolism or related to the bulking material, they are widely detected at composting facilities with different feedstocks. The dominant species detected in the biosolids composting studies were Ŭ-pinene and limonene (Van Durme et al., 1992, Maulini-Duran et al., 2013). Furans and esters were also identified in process emissions, albeit at low levels. It was suggested that levels were related to the low volatilisation rate rather than their ongoing formation (Maulini-Duran et al., 2013).

Table 25. Odorants associated with composting biosolids.

H_2S [1,2]	benzene[1]
methyl mecaptan [2,5]	ethylbenzene[1]
ethyl mercaptan [5]	styrene[1,6]
dimethyl disulfide [2,4,5,6]	toluene[1,6]
dimethyl sulfide [1,2,3,4,5]	xylene[1,6]
CS_2 [1, 3,4]	
COS [2,3]	chlorobenzene[1]
	dichlorobenzene[1]
ammonia [1,3,5,6]	1, 1, 2 - trichloroethane[1]
pyridine [1,6]	fluorotrichloromethane[1]
methylamine [5]	
trimethylamine [5]	cyclohexane[1]
	cyclopentane[1]
limonene[1,6]	2-ethyoxyethanol[1]
Ŭ-pinene[1,6]	
ƃ- pinene [6]	methylacetate[1]
	methyl chloride[1]
acetone[1,5]	acetaldehyde[1,5]
methyl ethyl ketone[1,5]	propionaldehyde [5]
heptanone[1,]	butyraldehyde [5]
cyclohexanone[1,6]	
2-pentanone [6]	heptane[1]
	nonane[1]
acetic acid[1,3,5]	octane[1]
formic acid [3]	pentane[1]
propionic acid [4,5]	
isobutyric acid [5]	methanol [1]
isovaleric acid [5]	phenol [1]
butyric acid [4]	n-propanol[1]

1. Van Durme et al. (1992) sampled emissions from blower exhaust and flux chambers on pile surfaces, analysed using colourimetry tubes, TenaxTA adsorbent tubes analysed using thermal desorption GC-MS and Jerome 631. Dilution olfactometry measurements also conducted.
2. VanderGheynst et al. (1998) measured emissions during lab/pilot scale composting using GC-FPD.
3. Rosenfeld et al. (2004) measured emissions from windrows and static piles from fluxchambers and negative pressure exhaust. Emissions analysed using GC-FPD, carbonate-bicarbonate impingers and analysis using HPLC-UV, sulfuric acid impingers and analysis using ion chromatography
4. Kim et al. (2005b) measured emissions from headspace of 14 composted products using SPME and analysis using GC-MS, selected ion monitoring of TMA and reduced sulfur compounds.
5. Lazarova et al. (2008) sampled the exhaust gas from 8 different facilities using 7 different technologies. Emissions were analysed using GC-ECD , GC-FID, acid colourimetry and GC-NPD, DNPH solution bubbler with HPLC-UV as well as desorption onto activated carbon or silica and analysis using GC-FID.
6. Maulini-Duran et al. (2013) measured emissions from composting exhaust using an ammonia sensors and SPME with GC-MS.

1.4.2. Process implications

Benedict et al. (1986) lists a number of recommendations for managing odour emissions from sites composting anaerobically stabilised biosolids. These findings are based on site visits and reviews of five composting facilities in America.

- Covering and cleaning trucks hauling biosolids
- Frequent scheduled deliveries of biosolids, to ensure frequent mixing
- At least 40wt% initial moisture in compost mix to ensure good ventilation
- Uniformly mixed, therefore porous material to prevent anaerobic regions
- Positive aeration can minimise emission as pile cover acts as odour scrubber
- Limit sludge volumes being processed
- Good management of pile tear down (not during early morning/wet weather to prevent inversions, or use high rate aeration prior)
- Effective liquid management
- Good housekeeping

Many of these recommendations generally apply to composting facilities. More specific relationships between process operation and emissions from the composting of biosolids are explored below.

1.4.2.1. Composting method

Aeration of piles can either be positive or negative, where the air is either forced (positive) or pulled (negative) throughout the piles. The latter obviously has massive advantages in terms of control of fugitive emissions given a high enough negative pressure. There are other issues such as increased blower wear due to the composition of the stream, while fugitive emissions will occur to a degree despite the method due to convective and diffusive emissions, as well as cycling of the blowers and material handling. A study of two full scale plants found that negative aeration could capture 65-69% of pile surface emissions compared to positive (Gould and Byers, 2002).

Aerated pile surface odours were reduced by negative aeration, due possibly to a reduction in fugitive emissions, and to an increased oxygen transport at the surface (Van Durme et al., 1992). Greater emissions of compounds such as ammonia, formic acid and acetic acid were measured using flux hoods from the surface of windrows compared to negatively aerated static piles (Rosenfeld et al., 2004)

1.4.2.2. Biosolids compositions and bulking agents

Epstein (1997) states that the type of feedstock influences odour emissions during the composting process, as readily digestible raw sludge produces higher intensity odours than digested biosolids. A number of studies compared the emissions from the composting of raw biosolids and anaerobically digested material and are outlined in Table 26. Differences between the two materials in terms of their processing, and emissions are based on the different ratios of C:N, due to the greater proportion of readily digestible organics. Epstein (1997) states that ammonia is often released from the composting of feedstocks with low C: N ratios <20:1. Raw sludge composting reached thermophilic conditions in under a day, returned to mesophilic conditions, and was considered stabilized after 12 days. However, the anaerobically digested biosolids weren't seen to reach thermophilic conditions. Likely as the sludge had already been stabilized in the wastewater treatment plant as the DRI (dynamic respiration index) wasn't seen to change (Maulini-Duran et al., 2013).

Rosenfeld and Suffet (2004) discuss that thermophilically digested biosolids produce more volatile fatty acid emissions than mesophillically digested biosolids, therefore use in composting would see more emissions through the composting process. The content of volatile organic acids was suggested to be an indicator of compost stability, their presence being correlated with microbial activity. As these organic acids have offensive characters, lower levels from stabilised products will have improved odour properties (Brinton, 1998).

Kim et al. (2005b) surveyed a range of composted products and noted that greater concentrations of reduced sulfur compounds were emitted from compost containing biosolids. This was compared to other organic streams such as food, manure and industrial and agricultural by-products. This effect can be attributed to the higher predominance of sulfur containing organic matter (proteins) in the biosolids.

Table 26. Studies comparing emissions from the composting of raw sludge or anaerobically digested sludge

Raw sludge	Anaerobically digested sludge	Reference
More NH_3 and VOCs Terpenes were emitted at levels above the OTV	More methane emitted (possibly due to stripping of CH_4 from AD) Low VOCs, possibly as the mass didn't reach as high a temperature.	(Maulini-Duran et al., 2013)
Constant emission in first 90hrs	Peak concentrations emitted in first 20hrs. More total VOCs during initial composting stage than RS	(Pagans et al., 2006b)
More VOCs emitted from the raw sludge's observed in plants, acetophenol was observed in large amounts.		(Van Durme et al., 1992)

The composition of the feedstock itself influences odorants released during composting. For example green waste was seen to emit different odours to biosolids as it contains more readily biodegradable compounds (sugars and cellulose) rather than the biosolids (Rosenfeld and Suffet, 2004, Defoer et al., 2002). The study by VanderGheynst et al. (1998) compares the emissions from composting biosolids with SFW (Solid food waste - dry dog biscuits). The authors observed that the dominant VSC emissions for the biosolids are DMDS and DMS (rather than MT for the SFW) and the time it took much less time for the emissions to peak. It was concluded that the higher level and varieties of bacteria present in the media due to previous treatment in the wastewater treatment plant were responsible, and the options of seeding the compost to increase microbial density was raised. Amlinger et al. (2008) identified that the addition of more mature compost to the initial material reduce emissions, however it should be noted that this was based on total VOCs rather than odour.

The combination of biosolids and yard waste also generated higher levels of propionic and butyric acid, thought associated with the anaerobic digestion of yard waste (Kim et al., 2005b). The high levels may be due to the high microbial population in the biosolids and high levels of biodegradables in the yard waste. Gutiérrez et al. (2014) linked the levels of biodegradable organic matter and odour concentration as measured by dynamic olfactometry.

1.4.2.3. Appropriate aeration and moisture control

In anaerobic conditions reduced sulfur and nitrogen compounds can form as well as volatile fatty acids, all of which can be highly odorous (Suffet et al., 2009). Anaerobic conditions can occur in three ways: the aeration method/rate is insufficient, high moisture levels limit oxygen transport and high rates of biological activity lead to oxygen being the limiting factor for growth (Maulini-Duran et al., 2013, VanderGheynst et al., 1998). The study by Rosenfeld et al. (2004) compared a windrow with an aerated pile and showed the better aeration of the latter reduced emissions of ammonia, formic acid and acetic acid considerably.

The use of absorbent additives such as wood shavings etc. can absorb water to favour degradation without depleting oxygen (DEC, 2004). The preferred moisture levels for composts range from 40 to 60% for operation, and 30 to 40% for sale of the product (Gutiérrez et al., 2014, Pagans et al., 2006b). Methane is commonly used to indicate oxygen deficiencies, and was seen in the first few days of composting of raw biosolids (Maulini-Duran et al., 2013). Other antecedent compounds (emitted before the main odorous compounds due to anaerobic conditions) are H_2 and CO (VanderGheynst et al., 1998).

1.4.2.4. Temperature and pH

Krogmann et al. (1997) detected a range of compounds emitted from biosolids composting and noted that the total VOC emissions increased as the composting temperature increased. Pagans et al. (2006a) also saw a dependency of ammonia emissions on temperature and recorded a near exponential increase of ammonia emissions when temperatures increased in the thermophilic stage.

The pH of the pile also influences the emissions, due to speciation of odorous compounds such as H_2S and NH_3. As the pH of biosolids is typically 8.5, H_2S will mainly be found as HS^-, a non-volatile soluble ion, which in aerobic conditions is readily oxidised (as well being able to be broken down by bacteria and fungi)(Rosenfeld et al., 2004).

1.5. Thermal treatment

Typically high odours are generated during the drying process; however these can be managed onsite. Emission patterns during drying are affected by the previous sludge history and the drying method chosen. The positioning of thermal treatment can be after other stabilisation processes such as anaerobic digestion or composting to obtain a superior class, reduce the volume for disposal or it can be used straight after dewatering raw sludge before incineration. From the literature reviewed the source of sludge was demonstrated to affect the types of odours emitted from product, especially when wetted or applied to land.

1.5.1. Odorants identification

The majority (70%) of the papers reviewed (n=10) characterised or monitored emissions from the drying process itself (Lazarova et al., 2008, Decottignies et al., 2010, Hoener et al., 2007, Fraikin et al., 2011, Muezzinoglu, 2003, Deng et al., 2009, Vega et al., 2015). The remaining papers studied the odour properties of the dried product, some studies including the effects of wetting and land application (Sivret et al., 2014, Rosenfeld et al., 2001a, Murthy et al., 2003b).

Few studies comprehensively identified odorants in emissions, the majority focused on the main sulfur based emissions (MT, DMS, DMDS, H_2S) (Table 27). A number of papers used olfactometry and the presence of a possible VOC has been raised by such authors who detected a ðburntò odour type however werenðt able to link it to a specific odorant (or group of odorants) (Lazarova et al., 2008, Decottignies et al., 2010).

Dried biosolids samples had more complex mixture of VSCs and more carbon disulfide and carbonyl sulfide (Sivret et al., 2014, Rosenfeld et al., 2001a, Murthy et al., 2003b). The greater variety of emissions was suggested to be related to the increased surface area of the dried biosolids enabling mass transfer and increasing biological activity when incorporated into soil (Rosenfeld et al., 2001a).

As the duration of drying processes are typically quick (< 8hrs) and temperatures high, compounds emitted during drying are those already present in the sludge or abiotically generated. Lazarova et al. (2008) identified ammonia as the major compound however emitted during drying. The emission of ammonia is likely dictated by factors such as pH, which affects the form of ammonia and the preceding treatment such as anaerobic digestion which generates large amounts of ammonium ions. TMA was released from thermally dried biosolids previously lime stabilized (Murthy et al., 2003b), this is to be expected due to the high concentrations released due to lime stabilisation (Kim et al., 2003).

The emissions of sulfur containing gases from low temperature pyrolysis of sewage sludge was investigated by Yang et al. (2012). The emissions of H_2S, SO_2 and MT were attributed to the transformation of organic sulfur, while CS_2 was thought to be due to interactions between FeS and methane. Emissions from dried biosolids pellets contain less reduced sulfur species such as carbon disulfide, carbonyl sulfide and DMDS (Murthy et al., 2003b).

VFAs are widely associate with the hydrolysis of sludge compounds during drying, the emissions are thought to stop when the sludge is dried as the hydrolytic action is decreased as water decreases (Deng et al., 2009). This corroborates the findings of (Murthy et al., 2003b) that volatile fatty acids (propionic and butyric acids) were released from heat dried undigested biosolids. Hoener et al. (2007) in a trial of an indirect rotary drum drying system measured H_2S and odour units of the emission stream. Based on the high OU results, other odorants apart from H_2S were suggested to be present. Lazarova et al. (2008) suggested that MT and TMA were the major contributors to drying process odours, based on their concentrations and odour detection thresholds. Ammonia and other sulfur compounds were only thought to be partially responsible. The range of odour descriptors of process emissions and from final product (e.g. burnt coffee, burnt rubber, garlic, medicinal, rancid) suggest a range of compounds contribute to the overall odour character (Table 27).

Table 27. Odorants and descriptors associated with thermally treated/stabilised biosolids

Odorants emitted during drying process	Odorants and odours emitted from dried product, when wetted or applied to land
hydrogen sulfide [1,3,5]	hydrogen sulfide[6]
methyl mercaptan[1,3,5]	methyl mercaptan [6,7]
carbon disulfide [5]	carbon disulfide [6,7,8]
dimethyl sulfide [1,2,5]	dimethyl sulfide[6,7]
dimethyl disulfide[1,5]	dimethyl disulfide[7,6,8]
dimethyl trisulfide[1]	dimethyl trisulfide[6]
ethyl mercaptan [3]	carbonyl sulfide[6,8]
propanethiol [2]	ethyl methyl sulfide[6]
sulfur dioxide [2]	methyl ethyl disulfide [7]
trimethylamine[1,3]	trimethylamine [7,8]
ammonia[1,3, 4]	
methylamine[1,3]	
dimethylamine[3]	
ethylamine [3]	
acetic acid[3, 4]	acetic acid [7]
propionic acid[3,4]	propionic acid [7,8]
butyric acid[1,3]	butyric acid [7,8]

Odorants emitted during drying process	Odorants and odours emitted from dried product, when wetted or applied to land
isobutyric acid [1,3] isovaleric acid [,3] valeric acid[,3] caproic acid[,3] isocaproic acid[,3] formic acid [4] ketones[1] acetone[1,3] 2-butanone [3] aldehydes[1] acetaldehyde [3] propionaldehyde [3] butyraldehyde [3] benzaldehyde [3] hexaldehyde [3] alcohols[1] methanol [3] propanol [3] butanol [3] terpenes[1] limonene[1] alkanes[1] heptane [4] alkenenes[1] esters[1] ammonia, burnt coffee, burnt rubber, manure, cabbage[3]	acetone [7] 2-butanone [7] phenolics [7] hydrocarbons [7] aromatics [7] terpenes [7] earthy musty, fishy, ammonia, smoke/burnt/grilled[1] strong putrid garlic odor[7] medicinal, ammonia, chlorinous, fishy, sour, decay, rancid, earthy, burnt, stale, garbage, petroleum [8]

1. Decottignies et al. (2010) evaluated emissions from a pilot sludge dryer. Emissions were analysed using GC-ECD, GC-FID, acid colourimetry and GC-NPD, DNPH solution bubbler with HPLC-UVD as well as desorption onto activated carbon or silica and analysis using GC-FID. Dryer emissions and the dried product were evaluated using Odour Profile Analysis for descriptors and intensities.
2. Muezzinoglu (2003) took ambient emission samples near a sludge drying bed, adsorbed emissions onto glass filters and analysed using GC-MS.
3. Lazarova et al. (2008) sampled the exhaust gas from 8 different facilities using 7 different technologies. Emissions were analysed using GC-ECD , GC-FID, acid colourimetry and GC-NPD, DNPH solution bubbler with HPLC-UVD as well as desorption onto activated carbon or silica and analysis using GC-FID
4. Deng et al. (2009) conducted batch drying tests using tubular drying furnace and sampled gaseous emissions using four different gas analysers
5. Vega et al. (2015) sealed 30g of dewatered biosolids in a 1L bottle which was heated at 85°C, headspace samples were analysed using GC ï PFP system and dynamic olfactometry
6. Sivret et al. (2014) incubated samples in sealed jars for one day then analysed using thermal desorption from a specialised cold trap and analysed using GC-SCD, samples were diluted for dilution olfactometry
7. Rosenfeld et al. (2001a) used flux chambers on land applied dried biosolids to gather emissions. Analysis was conducted using cryogenic concentration and thermal desorption then GC with two different columns (suitable for VFAs or VSCs) and mass spectroscopy
8. Murthy et al. (2003b) flushed headspace of 4 x 600g dried biosolids in 1L jar and collected Tedlar bags for olfactometric analysis (intensity, persistence, hedonic tone, descriptors) and reduced sulfur compounds using GC (ASTM D5504-98 method). SPME fibres were also exposed to off gas, analysed for trimethylamine and volatile fatty acids using GC-MS and GC-FID respectively

1.5.2. Process implications

1.5.2.1. Sludge origin

In a full scale study reported in Lazarova et al. (2008) and Bouchy et al. (2009) the initial pH was noted to influence ammonia and sulfur compounds emitted during drying. Due to the short residence times in the drying processes any compounds emitted were from the biosolids samples themselves, not being produced. Sludge that had been hydrolysed before drying, e.g. primary sludge or sludge that had been stored long-term emitted more degradation products such as hydrogen sulfide, methyl mercaptan as well as a range of VOCs.

Murthy et al. (2003b) evaluated the odour characters of dried sludge from a variety of origins such as lime stabilised WAS, undigested sludge, digested WAS and a combination of digested primary and WAS. The sensorial characters of the lime stabilised dried product was the most offensive (hedonic tone and intensity) thought due to the presence of TMA and ammonia, however these characters were rapidly dissipated when wetted or amended with soil. Undigested dried product was more offensive compared to digested counterparts. Odour emissions from undigested products deteriorated with moisture and soil addition producing VFAs and sulfur compounds, likely due to microbial activity. The character of digested dried pellets also deteriorated with wetting; however they had the least unpleasant hedonic tone compared to other sources, even though the odours were more persistent.

The effect of drying on emissions from anaerobically digested dewatered sludge from three different wastewater treatment plants were also evaluated by Sivret et al. (2014). Two anaerobically digested primary sludge or waste activated sludge or a combination of both. When the resultant biosolids were dried the product had a similar odour concentration, while the dewatered samples form the WAS site had much lower emission than the others, which are likely associated with lower H_2S and DMS.

Sivret et al. (2014) noted much higher levels of hydrogen sulfide to those noted by (Murthy et al., 2003b), this may be due to differences in the types of biosolids being dried, most likely the dosage of Fe salts, however because the papers used different drying temperatures and collection techniques this cannot be elucidated.

1.5.2.2. Temperature

Increasing temperature (140 ï 170ºC) increased the emission rate of compounds during drying. Condensers acted to remove 90% of alkanes and VFAs from exhaust streams (Deng et al., 2009). Emissions throughout the solar drying process are more similar to composting than other drying methods due to the long retention time (Lazarova et al., 2008).

1.5.2.3. Additives

Conditioners were added in a lab scale trial to evaluate their effect on odours during drying. Lime addition caused an increase in pH and reduced levels of MT and H2S emitted, but increase rates of DMDS. A combination of lime and iron salts were best, reducing total sulfur compounds and odour concentrations (Vega et al., 2015).

1.5.2.4. Wetting and land application

Sivret et al. (2014) noted that when the dried biosolids were wetted or mixed with soil the volatile sulfur compounds emitted into the headspace decreased. However, this effect wasn't matched with the odour concentration, suggesting other factors, such as masking, non-VSC odorants are responsible.

When dried pellets of different biosolid types were wetted hedonic tones became similar but emitted compound concentrations were reduced (Murthy et al., 2003b). The study concluded that thermal drying of lime amended biosolids produced the most offensive dried product, however when wetted and applied to soil this honour was bestowed upon un-stabilized pellets.

1.6. Alkaline stabilisation

Emissions from the alkaline stabilisation of biosolids were mostly measured during the stabilisation process, and only a few studies focusing on land application. Different sampling methods used were headspace (most popular, n= 13), then flux chambers and hoods (n= 3) and a mix between a flux chamber and headspace was used in two studies (sampling from inside a perforated pipe stuck into a bucket of biosolids). Two studies took ambient in-situ samples which were analysed using sensorial methods.

1.6.1. Odorants identification

The majority of studies have focused on measuring the typical volatile organic sulfur compounds MT, DMS, DMDS as well as H_2S, CS_2 and COS as shown in Table 28. In addition ammonia and TMA were commonly measured. Similar compounds were emitted from alkaline stabilised biosolids during stabilisation and storage as from land application; however there have been fewer studies into the field applied studies. Emissions from land application also included a range of aromatics and terpenes (Table 28). Papers not included in Table 28, are those that only reported single compounds such as TMA or DMDS (Chang et al., 2005, Gabriel et al., 2005), or only used sensorial methods of analysis (Mangus et al., 2006, Gabriel et al., 2006, Krach et al., 2008a).

The odours generated from lime stabilisation vary from those from anaerobically stabilized cakes due to the properties of the cake (pH, redox potential and biological activity). Initially high levels of ammonia are released, contributing ammonia type characters, latter these are substituted for fishy characters due to the presence of TMA (Murthy et al., 2001). Liming appears to favour the dimerisation of MT producing more DMDS after biosolids are limed, the reaction appears to be abiotic and is accelerated with increasing pH (Novak et al., 2002). Due to the increase in pH, ammonia in addition to TMA is released as its pka is exceeded, this may pose health risks if ventilation in inappropriate (Rafson, 1998). When applied to land and incorporate with soil, ammonia and amine emissions fell below detection threshold, likely due to the dilution, sorption and drop in pH(Laor et al., 2011). The land application sites had a sewage type odour compared to the soil type odour of control site, likened to DMDS and DMTS (Laor et al., 2011).

Due to the high pH of the limed biosolids emission of hydrogen sulfide is thought to be low as its converted into ionised non-volatile forms (Chao et al., 1996). No H_2S was detected in studies at Blue Plains WWTP which may be attributed to high pH or the large amount of iron salt dosing in the plant (Murthy et al., 2002).

Table 28. Odorants associated with alkaline stabilisation of biosolids, identified in the reviewed literature for emissions from onsite and land application.

Stabilisation / onsite storage	Land application
methyl mercaptan [1, 2, 3, 6, 7, 8, 9, 11, 12]	methyl mercaptan [12]
dimethyl sulfide [1, 2, 3, 4, 5, 6, 8, 9, 11, 12]	dimethyl sulfide [10, 12]
dimethyl disulfide [1, 3, 5, 6, 7, 8, 9, 11, 12]	dimethyl disulfide [10, 12]
H_2S [2, 3, 4, 13]	dimethyl trisulfide [10]
CS_2 [1, 2, 4, 5, 6, 7, 9, 12]	H_2S [12]
COS [4, 12]	CS_2 [10, 12]
butyl mercaptan [6]	COS [12]
isobutyl mercaptan [12]	isopropyl mercaptan [12]
isopropyl mercaptan [12]	
ethyl methyl sulfide [12]	ammonia [12]
	dimethylamine [12]
ammonia [13]	trimethylamine [12]
TMA [2, 3, 5, 6, 7, 9, 10, 12]	
diethylamine [12]	benzene [10]
triethylamine [10, 11]	toluene [10]
DMA [7]	ethyl benzene [10]
N-methyl pyrollidine [10]	xylene [10]
N-methyl piperidine [10]	Ŭ pinene [10]
	ɓ pinene [10]
	p-cymene [10]
	limonene [10]
	C9-C18 [10]

1. Abu-Orf et al. (2002) analysed headspace emissions using SPME with GC-MS, and onsite Jerome 631 for H_2S and an internal odour panel for intensity and hedonic tone.
2. Abu-Orf et al. (2004) analysed headspace emissions of stored biosolids using GC-MS
3. Subramanian et al. (2005) analysed stored headspace samples using GC-MS
4. Erdal et al. (2004) analysed emissions from land applied biosolids for a range of reduced sulfur

compounds, method not stated 5.Kim et al. (2003) used SPME and GC-MS to measure headspace odorants in lab stabilised biosolids 6. Kim et al. (2005a) used SPME and GC-MS to measure odorants in biosolids headspace pilot study 7. Krach et al. (2008b) measured odorants using GC-MS from headspace of lime stabilised biosolids 8. Murthy et al. (2002), Murthy et al. (2001) measured emissions from lime stabilised biosolids, gathered through a perforated PVC pipe stuck into the middle of biosolids. Tedlar bags were filled and were analysed using GC-MS and olfactory analysis 9. Novak et al. (2002)analysed limed biosolids headspaces using cryogenic concentration and GC-MS, as well as ion chromatography of TMA deposited on dionex and eluted using methanesulfuonic acid. 10. Laor et al. (2011) used SPME and GC-MS to measure headspace emissions from samples taken throughout a land application trial. Olfactometry conducted on samples taken using fluxhood onsite. 11. North et al. (2004) measured emissions from full scale limed biosolids using headspace sampling and GC-MS. Odour panels tested gas samples sampled using fluxhoods. 12. Easter et al. (2009)measured emissions from stored biosolids using fluxhoods and GC-FPD for reduced sulfur compounds, GC-MS for VOCs and adsorption tubes and GC-MS for amines and organic acids. Realtime monitoring using Jerome and Gastec and Draegar tubes for H_2S, ammonia and amines also used. Odour panels tested gas samples taken insitu 13. Butler et al. (2006) measured headspace emissions using GC-MS, Odour panels tested headspace gas samples, odorant results not reported

1.6.2. Process implications

Requirements for alkaline stabilisation are typically based on requirements for meeting and maintaining pH over time. Differences in operational practices include sludge origin, if the sludge have been digested or not, additive type, dose, incorporation method and location. These factors are interrelated and as they affect stabilisation (Krach et al., 2008b) as well as what compounds are emitted during the liming process, storage and from land application. Relationships between process variables and the reviewed literature relating to odour emissions are summarised in Table 29. As alkaline stabilisation is based on the microbial inhibition due to high pH, operational factors affecting odour emissions from the solids are typically concerned with stabilisation efficiency. Lime dosage as well as how its incorporated into the biosolids affect whether the pH will decay, this decay in pH can result in microbial growth and the production of odorous sulfur compounds. The evolution of these sulfur compounds therefore suggests an unstable product.

The origin of the sludge prior to alkaline stabilisation also affects odour emissions. Depending on the prior treatment, sludge sources have different content of organic matter (e.g raw sludge has more than digested sludge). Therefore, if microbial activity is present in the biosolids, the raw sludge or lower grade biosolids would present a greater odour risk due to their higher organic content as shown in Table 29.

Other sources of odours are those emitted from the biosolids due to the action of liming, rather than being produced by microbes, namely ammonia and TMA. These emissions are typically emitted immediately and can persist during storage, while sulfur containing odorants typically increase over time. The ammonia content of the sludge is dependent on the precious processing. Large ammonia emissions are expected from alkaline stabilised anaerobically digested biosolids as it's produced from the anaerobic degradation of proteins (Table 29). Certain polymers have been identified to produce TMA when microbially degraded. Longer storage of the polymer dosed biosolids prior to alkaline stabilised gives more time for TMA to form, while shearing also promotes its formation (Table 29).

Table 29. Operational factors noted to affect odours emitted from biosolids during and after alkaline stabilisation.

Operational factors	Mechanism and findings
Dosage	The amount of lime added to a biosolids processing plant was found by Gabriel et al. (2006) to have a strong negative relationship with biosolids odour generation potential Murthy et al. (2001) found that increasing lime doses decreased the OU/m^3, MT, DMS and DMDS concentrations. The panellists reporting fishy or putrid odours appeared independent of lime dose, suggesting lime dose affect VSC emissions more than TMA. Low lime dosing, targeting pH of 11 rather than 12, while satisfying faecal coliform regrowth/reactivation requirements, appears to generate more MT and DMS during storage compared to the control. However, the overall odour quality according to an odour panel is improved (Erdal et al., 2004). Likely due to lower emissions of TMA and ammonia due to the lower pH.
Lime incorporation	Many authors have identified that poor mixing of lime into the dewatered biosolids is responsible for the production of odours and odorous compounds, such as reduced sulfur compounds, during storage (Mangus et al., 2006, Murthy et al., 2002) Application of well mixed class A limed biosolids didnt result in significant odours and near neutral hedonic tones were observed on the site of field application (Krach et al., 2008a). This was noted with difficulties in lime incorporation in dewatered vs. thickened samples (Novak et al. 2002), MT was still generated in the dewatered samples. As MT is generated biotically it suggests lime wasnt well incorporated and stabilisation was not achieved The sensorial consequences of poor mixing dont appear to be considerable when incorporated into the soil, even though they are at the plant. For grade B biosolids, well mixed samples applied to land have a more ammonia odour, while rotten, putrid odour was typical of poorly mixed samples, class A biosolids had a neutral odour which was largely independent of mixing (Krach et al. 2008a).
pH decay	Sludge that was stabilised with a low lime dose and poor mixing produced more odorous emissions and the pH reduced over a month of storage. (Butler et al. 2006) North et al. (2004) noted poor incorporate and mixing of lime, while initially achieving a pH of 12, may have a faster pH decays and more odours due to areas of incomplete lime incorporation. If long periods of storage are required the lime doses need to be increased to prevent pH decay, an effect which is exacerbated by exposure to the atmosphere and microbial growth. Krach et al. (2008a) identified that the pH of poorly mixed limed biosolids decreased during storage and generated lower (worse) hedonic tones compared to well mixed limed biosolids.
Sludge origin	High inplant odours from settling tanks, likely due to DMDS, were associated with high emissions from lime stabilised biosolids (Murthy et al., 2001). Kim et al. (2003) identified a trend between odour (VSC) produced and the Oxidation reduction conditions in the thickening unit (DAF), which was also linked to temperature. In warmer temperatures, the more likely the unit process was to become septic, leading to the production of VSCs that can be released later in the processing. Gabriel et al. (2005, 2006) designed statistical models for the same plant and process studied by Kim et al. (2003) in which the sludge blanket depth in the secondary processing represented the ORP and was a strong indicator of odours (odour panel and DMDS) produced by the dewatered limed biosolids downstream on the following day. Another variable in the model that was seen to be strongly correlated to odour production was the number of centrifuges operating relative to belt presses (Gabriel et al. 2006), these would decrease the storage time of the liquid sludge. Storage, of up to 4 hrs, of unstabilised dewatered biosolids prior to liming increased emissions of TMA(Kim et al., 2003). Long term anaerobic storage or digestion of biosolids prior to stabilisation reduced the emission of VSCs from the limed biosolids Thought

Operational factors	Mechanism and findings
	to be related to the demethylation by methylotrophic methanogenic bacteria and the formation of less odorous H_2S and ammonia (Novak et al., 2002). Work by Subramanian et al. (2005) showed that dewatering of pre-limed sludge using full scale belt filter press have much greater initial TMA emissions and increasing reduced sulfur emissions with ageing compared to samples that were dewatering with vacuum filter in the lab. The difference was attributed to shear during dewatering.
Polymer addition, subsequent degradation	Increasing the dose of polymer (100% optimum dose) increased TMA concentration and worsened hedonic tone after two days of storage noted by Murthy et al. (2001). Suggested to be due to the degradation of amino acids and/or the degradation of polymers. Kim et al. (2003) identified the relationship between polymer dose, odour production, TMA concentration and the time before liming. This relationship suggests that the time before liming contributed to the generation of TMA, which when limed was released due to its pKa of ~9.5 at typical processing temperatures; the authors hypothesised the role of microbial degradation of the polymers as the source of TMA. Subramanian (2004) showed that the abiotic degradation of certain polymers is too slow to detect, however the biotic breakdown to TMA was shown in the lab. Aerobic incubation of NALCO 1404, a high molecular weight cationic polymer with a Polyacrylamide backbone with RAS and water for eight days prior to liming showed more TMA generated for the bottles with more polymer (Subramanian et al., 2005). This is likely to occur in both aerobic and anaerobic conditions. Shearing also appears to increase this production rate. Chang et al. (2005) furthered this research and identified that only certain polymers (PAM based containing amide or ester linkages) formed TMA when degraded, and went on to suggest that the first step in the degradation is microbially mediated as abiotic degradation tests showed no TMA production. However the degradation of choline, produced from polymers, was seen to occur abiotically.
Other additives	The level of iron in biosolids is related to the binding of polymers and the formation of FeS, preventing H_2S release. Gabriel et al. (2005, 2006) linked reduced sulfur odours with levels of iron in the biosolids cake. Woodash has been commonly added to biosolids to reduce the moisture content of alkaline stabilised biosolids, also seen to reduce odours (Stallings et al. 2005). Calcium nitrate and anthraquinones addition to lime amended biosolids was tested by Abu-Orf et al. (2002) and Kim et al. (2005a). Lab trials showed improved hedonic tone and odour intensity for ageing biosolids, however this effect was not seen to be significant in full scale trials (Abu-Orf et al. 2002). Full scale trials saw a reduction in methyl mercaptan (Abu-Orf et al. 2002), and total reduced sulfur (Kim et al. 2005a), however didn't appear to influence sensorial responses . This may be explained by the generation of TMA, which didn't appear to be affected by the treatments (Kim et al. 2005a)

2. Appendix 2 - Biosolids Risk Management, odour control and material stability and vermin/vector management

To satisfactorily convert sewage sludge into biosolids, and ultimately into a form suited to reincorporation into the natural environment e.g. soil conditioner a modern management framework was seen as required. The underlying idea was that full and complete recycling should be viewed and undertaken in an holistic manner where all processing, transport storage and final disposal is integrated and managed with this in mind. In support of this aim, this Appendix of the literature review explores the option that the new NSW guidelines for biosolids management might be adapted from, and be harmonized with, environmental management frameworks that have emerged since the previous guidelines were published (NSW EPA, 1997).

These frameworks have been captured in various environmental and risk management guidelines and standards. These documents capture potentially applicable management principles and methods, firstly conceptually in documents such as International Standards Organisation and Australian standards, and secondly operationally in various guidelines developed by the Australian Federal environmental management oversight bodiesô As biosolids are a product of the water industry those developed for water are particularly appropriate for harmonization and adaptation.

The review first looks at the concept of risk management. After outlining what risk assessment and management involves and identifying key features of current guidelines and standards, we discuss how risk management methods and systems might be adapted to create an odour (risk) management framework, in particular one based on:

- the Australian enHealth Environmental Risk Assessment (ERA) format (EnHealth Council, 2012b, National Research Council, 1983) for initial design of biosolids odour management and expected characteristics when management systems are operating nominally;
- ISO 31000 standard tools (Australian Organic Ltd, 2013, Standards Australia and Standards New Zealand, 2009, ISO, 2009, IEC/ISO, 2009) for situations where biosolids management goes out of specification e.g. generates unacceptable odours;

We then review the place of stability and vermin/vector management in such a scheme, discuss the place of modelling and some applications the guidelines might recommend and scoped how odour and stability issues may come directly under key ERA head of consideration (for details see Section 2.3.1). Finally we present a range of recommendations on features of future biosolids management guidelines.

2.1. How risk management offers an adaptable option for a biosolids odour and stability management framework

2.1.1. What is risk?

A framework can be conceptual or operational. That is a framework can be either as illustrated by the Oxford definitions (http://www.oxforddictionaries.com/definition/english/framework) *sic* :

ñ(A framework is) A basic structure underlying a system, concept, or text (e.g.) the theoretical framework of political sociology.ò (or) ;

ñan essential supporting structure of a building, vehicle, or objectò (e.g.) a conservatory in a delicate framework of iron.ò[1]

Risk assessment and management standards have now evolved to the point (IEC/ISO, 2009, ISO, 2009, Standards Australia and Standards New Zealand, 2013) where they provide both guidance on conceptualizing risks and operationally managing them.

Addressing the first need, ISO 31000 explains:

ñA risk management framework provides the policies, procedures and organizational arrangements that will embed risk management throughout the organization at all levels. As part of this framework, the organization should have a policy or strategy for deciding when and how risks should be assessed.ò

Addressing the second need, ISO 31010 provides a catalogue of diverse and complementary risk assessment and management tools (Standards Australia and Standards New Zealand, 2013) which for example variously address:

- ñRisk identification
- Risk analysisð assessing the effectiveness of any existing controls
- Risk analysisð consequence analysis.
- Risk analysisð qualitative, semi-quantitative or quantitative likelihood estimation.
- Risk analysisð estimating the level of risk.
- Risk evaluationò

Critically, the concept of óriskô is a more general one than often understood and so it conceivably can cover odour and stability in addition to the more familiar human or ecological health where water managers most often encounter the term. *Sic* (ISO, 2009):

ñrisk (is simply the[2]) effect of uncertainty on objectives

NOTE 1 An effect is a deviation from the expected positive and/or negative.

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[1] We interpret this to include method documents such as guidelines and standards which provide detail on agreed management procedures and so support management implementation in practice.

[2] Implication added by WRC

NOTE 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).

NOTE 3 Risk is often characterized by reference to potential events and consequences, or a combination of these.

NOTE 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.ò

2.1.2. Further reasons for considering a risk based framework for managing odour stability and vermin

Further reasons for exploring the option of a risk management based framework for odour and stability are that:

1. Many management guidelines dealing with water, solids and air protection have now successfully adopted a risk management framework demonstrating the effectiveness of the general approach.
2. Implementing such a framework style, in principle would have the benefit that the lessons learned in analogous and related environmental management fields could be justifiably transferred or adapted to biosolids management.
3. WRC understands adaptation of risk management systems including human health risk assessment (also known as environmental risk assessment) is already being proposed for the management of pathogen and toxic chemical exposure in the new biosolids guidelines.
4. The USEPA (1995) advice on Guidelines management commences (p3) with a description and promotion of ERA as the basis for assessment biosolids suitability and itemization of management activities (p. 4). Thus employment of a risk management based framework would be in line with overseas recommended practice;
5. NSW EPA appears to wish to move in this direction for odours generally and the 1997 Biosolids guidelines were explicitly seen as an interim step on the way to risk management guidelines:

"These guidelines are a step towards producing revised guidelines based on risk assessment" (NSW EPA, 1997).

2.1.3. Initial impressions from literature examination on the applicability of risk management

From WRCõs examination of the literature it appeared that risk management methods and ideas are indeed largely applicable to odour control and material stability management. That said it appears there would also need to be some clarifications and modifications to address, for example, how odour should be benchmarked, or thought of given it is not a classical human physiological health risk in the sense of causing physiology disease and disability. As importantly the concept of ‘stability’ does not as yet appear to have been scoped sufficient to provide benchmarks suited to an operational risk management framework.

In the end how odour and stability concepts would be incorporated into the guidelines is for NSW EPA to decide. So this review aims to support its decisions and directions by exploring and explaining how odour and, in a different fashion stability, might fit into a risk assessment and management framework. It aims in particular to outline how an environmental risk management framework and tools might provide a model and identify how the EnHealth Environmental Risk Assessment (ERA)[3] scheme could be applied to odour and stability management. To do this the remainder of this Appendix is structured as follows:

- It outlines developments in risk management probably applicable to odour and stability management – section 2.2;
- It discusses the implications of adapting the environmental risk assessment framework to odour management and what a changeover might entail using primarily Environmental Risk Assessment / HACCP heads of consideration – section 2.3;
- It discusses the question of stability and vectors/vermin bearing in mind ERA and risk management more generally - section 2.4;
- It discusses the place of modelling – section 2.6.

2.2. Developments in risk management since 1997

This section describes developments in the field of risk management which in WRC's opinion support the application and adaptation of risk management tools to biosolids odour, stability and vermin management.

2.2.1. How risk management style analysis offer many paths for improving biosolids odour and stability management even if the latter are not classical risks

Since the previous NSW biosolids management guidelines were developed (NSW EPA, 1997), there have been a range of conceptual advances in methodologies guiding microbial and chemical assessment and management e.g.:

- The refinement of environmental management principles and methods;
- An exchange of learning and harmonization between different guidelines (e.g. between water and food guidelines);

[3] Includes toxicological and eco-toxicological risk assessment and quantitative microbial risk assessment

- Tighter/more explicit linking of monitoring to management e.g. (Department of Health and Aging, 2002);
- The basing of action targets and endpoints on the satisfactory management of key issues especially risk, rather than monitoring data endpoints.

The adaption of these developments to biosolids seemed feasible also because, like environmental and health risk assessment and management of the microbial and chemical quality of water and wastewater, the assessment and management of biosolids stability and odour increasingly:

- employs analytical and other objective scientific measures to quantify the extent of stability and scale of emission impacts e.g. use of chemical and biological assays and modelling;
- employs statistical methods for analysing data generated by comparable monitoring technologies;
- aims to relate monitoring to potential impacts on human populations under a range of scenarios;
- (and thereby also) aims to relate monitoring data to management.

i.e. the implementation process and general intent of biosolids odour and stability management and diverse risk management based guidelines are largely the same.

2.2.2. DEHC concurrence with applying a risk management (based) framework to odour management

NSW DEH in their general framework for assessing and managing odour (Department of Environment and Conservation (NSW), 2006a) have proposed that:

ñOperators of all (biosolids?) developments should adopt a risk management approach é é é . because addressing odour impacts retrospectively is likely to be difficult and costlyò

In addition to providing further general odour management technical notes (Department of Environment and Conservation (NSW), 2006b), DEH goes on to say:

ñThe criteria used in this framework have been selected to protect the majority of the population living within the vicinity of activities that emit odour.

1 Ground-level concentration (glc) criteria. These are applicable to individual odorous pollutants. The framework adopts the glc criteria in **Approved methods for the modelling and assessment of air pollutants in NSW**, which are based on odour threshold or toxicity threshold (whichever is more stringent). They are used to assess the likely performance of a project and acceptability of impacts at any location beyond the boundary of a premises.

2 **Odour assessment criteria**. These are applicable to complex mixtures of odours. The framework adopts the odour assessment criteria in **Approved methods for the modelling**

and assessment of air pollutants in NSW. They are used to assess the likely performance of a project and acceptability of impacts at the nearest places where people are likely to work or reside (both existing and any likely future sites). These places are referred to in subsequent instances as ósensitive receptorsô or, more simply, óreceptorô (see glossary). If a receptor is, or is likely to be, located near the boundary of premises that emits odour, then the criteria should be applied at and beyond the boundary of the premises. The appropriate criterion for a single affected residence is deemed to be a concentration of odour equal to seven times the theoretical minimum necessary to produce an olfactory sensation. This can be expressed as 7 odour units (7 OU). For receptors that have larger populations, in which there will be a greater range of sensitivities to odour (and a higher number of more sensitive individuals), acceptable odour is defined as 2 OU.ò

ñOdorous air pollutants that have predictable health-related impacts are more appropriately managed as individual pollutants and should be assessed against the glc criteria. For complex mixtures of pollutants, the impact should be assessed against the odour assessment criteria.ò

These above quotes are significant for three reasons. Firstly they identify a central support document (Department of environment and Conservation (NSW), 2005), DECôs guidance on assessing toxic volatiles and odour emissions, transport and impact which are essentially methodologies for óExposure Assessmentô a process central to ERA risk assessment and management.

These documents clearly recommend objectively measurable odour target values and hence the principle of using exposure concentrations as benchmarks in determining management.

Finally these NSW EPA documents indicate quantification of odour via air transport modelling is considered best practice.

2.2.3. Risk management related guidelines which could provide model procedures for biosolids managment

In the previous guidelines microbial, chemical and biosolids stability and odour control were treated as separate problems (NSW EPA, 1997). In the period since then:

1. Environmental (risk) assessment has been more tightly and explicitly linked to management:
    a. e.g. as with the enHealth Guidelines (Department of Health and Aging, 2002, EnHealth Council, 2012a, EnHealth Council, 2012b) which were based on the US Environmental Risk Assessment Methodology (National Research Council, 1983)

2. Guidelines from different disciplines have learnt from one another and adopted one another's good or common features, a process referred to by the United Nations as 'harmonization' e.g.
    a. The drinking and recycled water industry recognized that their product was similar to that of food, and so adapted the Hazard Analysis and Critical Control Point and environment risk assessment systems (Notermans et al., 1995, Codex Alimentarius Commission, 1999, WHO and FAO, 2011, National Research Council, 1983). The latter was developed itself originally for NASA (Hulebak and Schlosser, 2002) adopted and developed analogous risk based guidelines and management tools (Havelaar, 1994, Environment Protection and Heritage Council, 2006, NH&MRC NRMMC, 2004, Bartram, 2009).
3. There has been a movement toward measures which are more closely related to actual impacts e.g. risk, and away from more general environmental quality variables e.g. convenient water quality analysis measurements which are now used instead to infer the former measures i.e. analytical data is used to infer risk.
    a. e.g. The early bathing water guidelines focused on indicator water quality. The modern equivalents still use monitoring but use the data to infer bathing water quality category and from there bathing locality class when combined with sanitary status (compare National Health and Medical Research Council, 1990, NH&MRC, 2008).
4. There has been a movement toward incorporating an understanding of the interactions with, and occurring in, the built and natural environment e.g.:
    a. See again bathing water comparison. Another example is drinking water guidelines which is based on the "Catchment to Consumer" analysis e.g. (Nadebaum et al., 2004).
5. Chemical and microbiological contaminant management have moved towards a common (risk) measure, the Disability Adjusted Life Year e.g.
    a. The movement toward assessing health risk based on the common measure of the DALY which is applicable to both these contaminants and many other risks (Gao et al., 2015, Timm et al., 2016, Havelaar et al., 2000, Murray et al., 2012, Stouthard et al., 1997, Pruss and Havelaar, 2001 , Prüss-Ustün et al., 2011, Havelaar and Melse, 2003)
6. There has been the movement towards guidelines being based on common principles e.g.
    a. Many management tasks now fall under the auspices of 'Risk Management'. Earlier guidelines on risk developed in the 1990s and 2000s (Standards Australia/Standards New Zealand, 1999, Standards Australia International,

2004, Standards Australia/Standards New Zealand, 2004b, Standards Australia/Standards New Zealand, 2004a) were recognised to operate in common ways but newer versions are much broader in scope - compare (ISO, 2009, Standards Australia and Standards New Zealand, 2009, IEC/ISO, 2009, Standards Australia and Standards New Zealand, 2013);

2.2.4. Environmental Management System Standards

Complementing risk assessment developments are guidelines for achieving high quality products which indirectly aim to manage risk of production failures.

In business generally where a clear product is identifiable, there has been a push for the producer organization to do this comprehensively and systematically with the aim of consistently achieving a high quality product with minimal external impacts and waste. This has been formalized through the ISO 9000 quality management series of standards (e.g. ISO, 2005, ISO, 2008). This aim of achieving high quality products with minimal impact has been transferred to products where there are significant environmental impacts via the related ISO 14000 standards. These are designed to promote the development of comprehensive and standardized ‘Environmental Management Plans’. The methods for developing sound environmental plans can be found in the various Environmental Management System (EMS)[4] standards: e.g. (ISO, 2004a, ISO, 2004b, ISO, 2006, ISO, 2010, ISO, 2011). Noteworthily ISO 9000 and 14000 were initially rolled out in the mid 1990s more or less concurrently with the NSW Biosolids guidelines making their incorporation impractical.

EMSs are not the same or alternatively as risk management plans. Rather they provide a larger framework within which (risk) management of biosolids odour stability and vermin logically sits as evidenced by this introductory section from ISO 14001:

“Organizations of all kinds are increasingly concerned with achieving and demonstrating sound environmental performance by controlling the impacts of their activities, products and services on the environment, consistent with their environmental policy and objectives They do so in the context of increasingly stringent legislation, the development of economic policies and other measures that foster environmental protection, and increased concern expressed by interested parties about environmental matters and sustainable development.

Many organizations have undertaken environmental review or audit to assess their environmental performance. On their own, however, these reviews and audits may not be sufficient to provide an organization with the assurance that its performance not only meets,

[4] This topic complements risk assessment. It is reviewed briefly in the Appendix following this one.

but will continue to meet, its legal and policy requirements. To be effective, they need to be conducted within a structured management system that is integrated within the organization.

International Standards covering environmental management are intended to provide organizations with the elements of an effective environmental management system (EMS) that can be integrated with other management requirements and help organizations achieve environmental and economic goals. é .

This International Standard specifies requirements for an environmental management system to enable an organization to develop and implement a policy and objectives which take into account legal requirements and information about significant environmental aspects. It is intended to apply to all types and sizes of organization and to accommodate diverse geographical, cultural and social conditions. é é The success of the system depends on commitment from all levels and functions of the organization, and especially from management. A system of this kind enables an organization to develop an environmental policy establish objectives and processes to achieve the policy commitments, take action as needed to improve its performance and demonstrate the conformity of the system to the requirements of this International Standard. The overall aim of this International Standard is to support environmental protection and prevention of pollution in balance with socio-economic needs. It should be noted that many of the requirements can be addressed concurrently or revisited at any time.ǿ(ISO, 2004a)

This current Appendix is designed to review risk management applicability to odour stability and vermin. But as it is also relevant how EMSs might support managing biosolids satisfactorily. So the subject of biosolids management and EMSs is reviewed and discussed in the Appendix following this one.

2.2.5. The sea change driving this biosolids guideline evolution

2.2.5.1. Explicitly linking monitoring to management

An underlying sea change in environmental guideline style can be seen by comparing the 1990s guidelines e.g. NHMRC bathing water (Department of Health and Aging, 2002) and ANZECC (ANZECC, 1992) fresh and marine water quality guidelines, with their 2000s successors (ANZECC and ARMCANZ, 2000, NH&MRC, 2008).

The change in short has been to replace the focus on parameter measurement and monitoring with ones supporting problem/issue control/management/solving.

This change reflects a simple but subtle conceptual shift. This is that the point of guidelines and the scientific effort put into supporting them (e.g. monitoring) is not to collect data *per se* or (solely) to understand a systemõs structure and function[5], but rather the utilitarian aims of promoting good, healthy and well-functioning human and natural environments and human interaction and stewardship of them i.e. guidelines and monitoring are means to an ends which operationally are as follows:

1. Environmental guidelines and monitoring are aimed at promoting ŒEnvironmental Valuesö[6];
2. This is achieved by good management informed by monitoring data and also less routine studies rather than exhaustive collection of large quantities of repeat measurement indefinitely ï i.e. routine monitoring;
3. The new environmental guidelines are designed to capture the key management and monitoring activities, drivers, endpoints etc. and their interrelationships in a concise authoritative form so that operational managers overseeing human disease control (e.g. health surveyors) and ecological protection (e.g. wildlife officers) donõt have to óreinvent the wheelô or second guess regulator requirements when undertaking their jobs day to day.[7]

This change could be seen emerging in the early 1990s when for example the ANZECC water quality guidelines (ANZECC, 1992) introduced their task with a brief description of ŒEnvironmental Valuesô and identification of ones was particularly concerned with water - e.g. protection of aquatic ecosystems, protection of human health/drinking water quality, protection of bathing water quality, protection of groundwater (resources), protection of industrial water quality. At the time though monitoring was still the focus, however, with detailing of analytical testing still dominating the guideline text. The interim NSW Biosolids guidelines appear to be a transitional document reflecting this change in that much focuses on test parameters but with increasingly detailed recommendations on best practice management. Since then the status of the strategic objective ï supporting Environmental Values ï has become still more central.

2.2.5.2. Some illustrative change case studies

Though in hindsight better environmental protection was always their goal, the central driver of management was arguably less well spelt out in the early days of the Clean Air and Water

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[5] In the 1970s when the first clean water and clean air acts were promulgated much less was understood about the environment generally, the subtlety of impacts and the competing forces driving environmental degradation e.g. pursuit of natural resources.

[6] See below for definition and discussion of the Environmental Values concept and its relevance to odour and stability management.

[7] One downside is the new guidelines are much larger and comparable to textbooks in size. But this is probably inevitable as the problems being managed have proved complex and vary from place to place over time. On the upside the new generation of guidelines tends to be much more authoritative and scientifically defensible and should make sense to a manager who understands the core science.

Acts. So monitoring was more seen as supporting legal regulation and monitoring evolved into something of a óstamp collectingô exercise with the guidelines providing only limited guidance on how to interpret and use monitoring data and combine different data sources.

In the 1990s this incomplete link between monitoring, data interpretation and management was increasingly recognized by the scientific community as being insufficient. The overall response that emerged was to better target monitoring. By 2000 the developers of the ANZECC guidelines (ANZECC and ARMCANZ, 2000) recognised the magic number issue well and recommended a óriskô approach as the best alternative. While this regulatory ómagic numberô number approach still persists today in the form of legacy licenses e.g. pollution discharge. The following from the latter guidelines illustrates how out of date the concept is:

ñThe guideline trigger values are the concentrations (or loads) of the key performance indicators, below which there is a low risk that adverse biological effects will occur. The physical and chemical trigger values are not designed to be used as **‘magic numbers’** or threshold values at which an environmental problem is inferred if they are exceeded. Rather they are designed to be used in conjunction with professional judgement, to provide an initial assessment of the state of a water body regarding the issue in question. They are the values that trigger two possible responses. The first response, to continue monitoring, occurs if the test site value is less than the trigger value, showing that there is a ólow riskô that a problem exists. The alternative response, management/ remedial action or further site-specific investigations, occurs if the trigger value is exceeded ð i.e. a ópotential riskô exists.ò

This movement to improving monitoring links to management is illustrated by the following case studies.

2.2.5.3. Recreational water management guidelines

The current Australian and NSW guidelines for environmental water bathing are modelled on a WHO model (World Health Organization, 2003). The latter in turn emerged from WHOõs Annapolis Protocol initiative (World Health Organization and Sustainable Development and Healthy Environments, 1999). The preface to the latter document concisely captures the change process and drivers.

ñDuring the development of Guidelines for Safe Recreational-water Environments concerns were repeatedly expressed regarding the adequacy and effectiveness of (1990s) approaches to monitoring and assessmenté é (further)é ..Despite evident successes in the protection of public health, present approaches to the regulation of microbiological hazards in recreational waters suffer a series of limitations. During the preparation of Monitoring Bathing Waters the United States Environment Protection Agency (USEPA) therefore supported WHO in organising an expert consultation **to look into the adequacy and**

effectiveness of present approaches to monitoring and assessment linked to effective management of microbiological hazards in coastal and freshwater recreational waters**.** The meeting was implemented in November 1998 in Annapolis, USA. The experts that met there agreed that an **improved approach to the regulation of recreational water that better reflected health risk and provided enhanced scope for effective management intervention was necessary and feasible**.ö[8]

This example illustrates the drive to link monitoring to management in support of better support for the Environmental Value of ósafeô natural bathing and recreation. The results illustrated by NH&MRC (2008) include:

- Recognition of different sources of contamination and the need to manage then differently e.g. discharged effluents with different quality different distances from bathing areas;
- Recognition of monitoring data limitations and addressing these in part via introducing complementary sanitary surveys designed to understand the primary hazard and risk ï on ground sanitary status assessment and improve data interpretation;
- Clearer guidance on assessments based on multiple factors using for example a risk assessment matrix.

WRC sees the implication for stability and odour management as being a need to clarify what strategic goals should be targeted by monitoring in the forthcoming guidelines i.e. how to best support ŒEnvironmental Valuesö.

2.2.5.4. HACCP, food safety management and drinking water protection

A similar change in focus has occurred in the food industry. As with water, a number of disease outbreaks had occurred over the years and the old monitoring data based regulation style/focus was seen as insufficient. The result was the introduction and roll out of the Hazards Analysis and Critical Control Point or HACCP system (Hulebak and Schlosser, 2002, Notermans et al., 1995, Notermans and Mead, 1996, Codex Alimentarius Commission, 1999, WHO and FAO, 2011). This much more holistic approach (that is management based on an understanding of the whole food production system from ïfield to forkö) had been developed for NASA recognising they could ill afford food poisoning on space missions. Again there was increased focus toward including ócorrective actionsô i.e. management in response to targeted monitoring (at critical control points). The critical feature of analysis of the complete food production process is essentially the same as environmental risk assessment which evolved more from concerns about toxic waste sites

[8] WRC emphasis

(National Research Council, 1983). The principle difference in the end seems to be that the terminology and principles are slightly different reflecting differences in the problem of concern i.e. protection of food to be consumed v. toxic waste whose ingestion/inhalation is to be avoided.

Increasingly in HACCP, emphasis has been put on probabilistic quantification especially of risk itself, in addition to collection of measurements of monitoring parametric indicators such as microbial counts:

"Risk management is the complex of analyses and judgements which aim to reduce the probability of occurrence of unacceptable risks. This definition implies that attempts to control such risks are carried out in a cost-effective manner." (Notermans and Mead, 1996)

One problem that food (and water) HACCP seems to address in particular is the logistics problem of representative sampling. Paul Gale (2002) provides a useful illustration of how 'small' system failures which end point monitoring cannot feasibly detect can still have big consequences in the case of water contamination. While regulators can specify the quality required of a food product, in reality determining this is constrained by monitoring costs. Food contamination can be very localized and so small samples from a big product stream can easily miss significant contamination.

This same problem is potentially faced in biosolids management where monitoring sample sizes must necessarily be tiny compared to the quantity of material needing to be put to beneficial reuse. For this reason 'end point testing' of final products too often failed. Further consistent mixing and treatment of biosolids e.g. liming is reportedly difficult to achieve and so requires special recognition in monitoring schemes.

The HACCP system has the further benefit that its can determine whether if one barrier fails another one can still be sufficiently protective. HACCP can conceptually provide a useful framework for understanding "hazardous events" e.g. because of unusual weather conditions odour plumes can be concentrated and impact much more severely than average exposure conditions might indicate.

A further benefit of HACCP style analysis has been the promotion of risk modelling both conceptually as well as operationally (Strachan et al., 2005, U.S. Environmental Protection Agency and U.S. Department of Agriculture, 2012). HACCP promotes better understanding of system failure scenarios including rare but high impact events which are impractical or extremely expensive to detect and understand via routine monitoring. **An important implication here is that the management of biosolids odours and stabilisation needs to be based on well validated models which are fit for purpose e.g. reliably assessing nuisance to a community.** It is notable that despite the increasing popularity of air modelling in the odour management community the term ómodelô is completely absent from the current guidelines (NSW EPA, 1997) .

The food HACCP approach was subsequently adapted to the drinking, recreational and wastewater management by the water industry (Havelaar, 1994, NH&MRC NRMMC, 2004, Environment Protection and Heritage Council, 2006, NH&MRC, 2008) especially in Australia in the wake of overseas and local incidents such as those involving *Cryptosporidium* and other water borne pathogen outbreaks and incidents (McClellan, 1998, Cox et al., 2003, Mackenzie, 1994, Hrudey et al., 2003).

The transfer of HACCP and Environmental (Health) Risk Assessment to drinking water illustrates how it is possible for risk management principles and methods to be readily transferred from one application to another and the very general nature of the risk management concept. **This lesson seems pertinent to new odour and stability guidelines development.**

These *Cryptosporidium* outbreak examples also illustrate why (risk) management is arguably superior to traditional black letter law/magic number based regulation based on often very few analytical measurements. This is because they address risk analysis routine considers the problem of uncertainty (IEC/ISO, 2009). In the case of *Cryptosporidium,* its potential for causing outbreaks due to chlorine resistance was understood prior to 1994/1998 in that it was recognised to be extremely chlorine resistant and infectious *C. parvum* was excreted by wild and domestic animals into catchment waters in high numbers as well as being found in sewage. But routine monitoring/risk assessment was based primarily on coliform bacteria which in contrast are very sensitive to chlorination and so were a poor indicator of such contamination risks (see for example Hansen and Ongerth, 1991, LeChevallier and Au, 2004).

This constraint of endpoint monitoring would likely have been recognised if a whole of system analysis had been undertaken and responded to earlier. The problem of such uncertainties is probably captured most famously by one Donald Rumsfeld:

*"Reports that say that something hasn't happened are always interesting to me, because as we know, there are **known knowns**; **there are things we know we know**. We also know there are **known unknowns; that is to say we know there are some things we do not know**. But there are also **unknown unknowns – the ones we don't know we don't know**. And if one looks throughout the history of our country and other free countries, it is the latter category, that tend to be the difficult ones". (Wikipedia)*

While the public ridiculed Rumsfeldøs comments as gobbledegook it is a standing joke among risk assessors that he was essentially correct and uncertainty analysis and reality checks are a central feature of risk assessment (e.g. EnHealth Council, 2012b).

Dealing with uncertainty is not a problem for scientists who routinely deal with it in the form of statistics. However, it presents a challenge for regulators trying to decide where a decision point lies, and the public is notoriously poor in their understanding of uncertainty as illustrated by the current battles over whether climate change science and modelling is reliable. **In the case of odour this means strategies will be needed to communicate the uncertainty associated with assessments during public consultation as well as the rationale for odour benchmarks.**

2.2.5.5. 'Monitoring Tailor Made' consortium

A final case study relevant also to biosolids odour and stability is that of the Monitoring Tailor Made (MTM) Consortium. In a series of 4 workshops this collective of water quality experts looked for solutions to challenges thrown up by ecological water quality monitoring limitations which became evident in the 1990s. For example it was recognised that they need to supplement traditional physicochemical monitoring with biomonitoring concurrent with monitoring budgets being under increased pressure. Their assessment provides many insights into the rationale behind good v. poor monitoring practice.

This (now dormant) European focused consortium generated a large number of concise insightful papers (Adriaanse, 1994, De Jong, 1994, Klapwijk et al., 1994, McBride and Loftis, 1994, Van Leeuwen, 1994, Ward, 1994, Adriaanse, 1997, Hotto et al., 1997, Kristensen and Krogsgaard Jensen, 1997, Van Luin and Ottens, 1997, Wiederholm and Johnson, 1997, Wilkinson, 1997, Ravera, 2001, Timmerman and Cofino, 2001, Broeders, 2003, MTM Consortium, 2007)[9].

The consortium recognized that the range of possible monitoring technologies was exploding and there were many different types of monitoring with different functions whose different roles were not always clear. The strength of the consortiumœs work lay in their assessment on what monitoring did or should involve and their recognition of the need to link monitoring to management to policy prior to introduction of risk management as an explicit policy driver [e.g. as seen for example in ANZECC and ARMCANZ (2000)]. These insights are reproduced below in figures extracted from Adriaanse (1997) **which capture key considerations that in WRC's opinion could be applied to future odour and stabilization guidelines**:

- Figure 12a sets the larger context for any monitoring. **Odour and stability management guidelines will need to address or recognise analogous heads of consideration**. The ones itemized provide a starting checklist for different

[9] These papers appear to no longer be available on line but WRC has a complete collection available on request.

odour and stability monitoring topics noting. It highlights how monitoring will involve not only scientific analysis but checking of management systems as well.

- Figure 12b illustrates how there are distinctive types of monitoring appropriate to different stages in the policy development and implementation cycle – **in the present instance guideline development and rollout**. The introduction of new guidelines will likely highlight knowledge gaps needing to be filled before a revamped biosolids odour and stability management regime is established. This will take time and need to involve the industry. In the long run the industry should settle mostly into routine (i.e. Operational) monitoring. **Odour and stability guidelines on monitoring should recognise these different forms of monitoring and their functions.**
- Figure 12c highlights a critical issue for the biosolids recycling industry. Monitoring is costly and should only be undertaken to a level sufficient for purpose and be subject to cost benefit considerations. **Odour and stabilisation monitoring techniques need to be grouped by cost and logistics as well as function with management aims directing where monitoring is prioritized**.
- Figure 12d outlines monitoring classification/checklist/grouping in a slightly different format which also highlights how there are different types "monitoring". This classification seems applicable to biosolids and could be used to assist communication between biosolids producers, disposal method operators, transporters, regulators etc. It provides a rationale for any research needed as well (strategic monitoring) and how it differs from more day to day early warning and process control monitoring. **A feature of the guidelines could be identification of examples of each as they relate to odours and stability.**
- Figure 12e outlines how information is collected and transferred to management essential in a cyclic fashion. This supports the need for risk management to be undertaken within a larger environmental management system[10] (ISO, 2004a, ISO, 2004b, ISO, 2010, ISO, 2011) designed to cover odours and stabilisation.

[10] See next Appendix

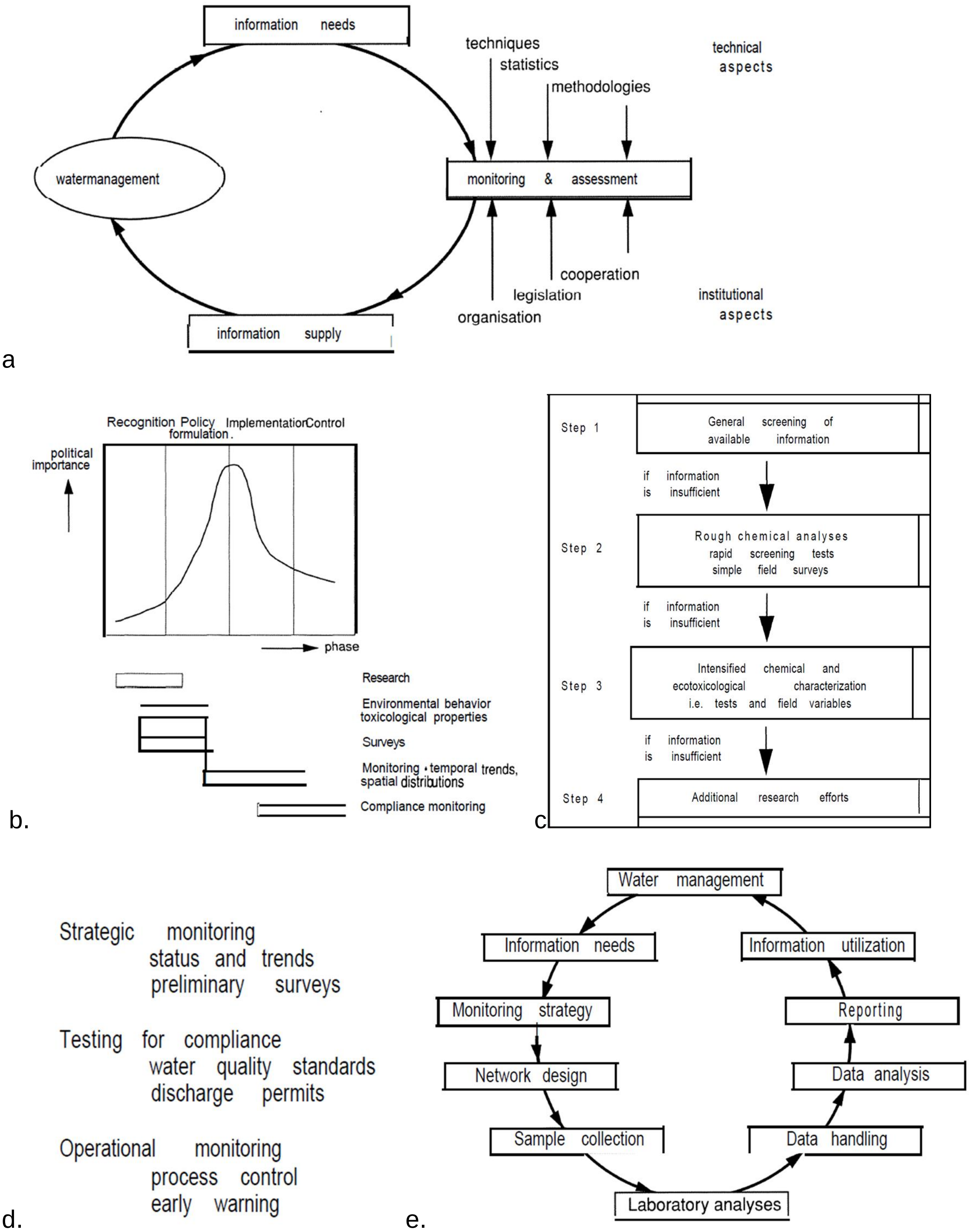


Figure 12. Key monitoring considerations (reproduced from Adriaanse, 1997)

a. Management tools
b. Monitoring needs and types in relation to the policy cycle
c. Tiering of monitoring
d. Monitoring types
e. The monitoring cycle

2.2.6. Environmental Values

In environmental management ‘Environmental Values’ constitute the top level strategic objective that captures what management activities aim to support. The concept was introduced in the 1992 Australian fresh and marine waters guidelines (ANZECC, 1992). However the concept did not find its way into the later Biosolids guidelines (NSW EPA, 1997). WRC suggests this concept might be included in new biosolids guidelines for reasons discussed here.

A starting point is to understand what is meant by ‘value’. There are many possible meanings but a defensible starting point is the following definition identified in a review of the topic of Environmental Values by Reser and Bentrupperbäumer (2005):

“Values are defined as prescriptive beliefs about end states of existence (e.g., peace) and modes of conduct (e.g., justice) that transcend specific objects and situations and that are held to be personally and socially preferable to opposite end states of existence (e.g., war) and modes of conduct (e.g., injustice) (Rokeach, 1973).” (Reser and Bentrupperbäumer, 2005)

Summary of geodiversity values (Gray, 2004)

Intrinsic value	1. Intrinsic value	Abiotic nature free of human valuations
	2. Folklore	Giant’s causeway, UK; devil’s tower, USA
	3. Archaelogical/Historical	Petra, Jordan; Stonehenge, UK: local tools and artefacts
	4. Spiritual	Uluru, Australia; N.American Indian sites
	5. Sense of place	White Cliffs of Dover, UK; Rock of Gibraltar; local places
Aesthetic value	6. Local landscapes	Sea-views; countryside walks; vernacular buildings
	7. Geotourism	Grand canyon, USA; Norwegian fjords; Canadian Rockies
	8. Leisure activities	Rock climbing; caving; whitewater rafting; fossil hunting
	9. Remote appreciation	Nature in magazines and TV; “Walking with dinosaurs”.
	10. Voluntary activities	Wall repairs; footpath construction; mine restoration
	11. Artistic inspiration	Literature (Hardy); music (Sibelus); painting (Turner)
Economic value	12. Energy	Coal & peat; oil & gas; uranium; geothermal; hydro-electrical; tidal
	13. Industrial minerals	Potash; fluorspar; kaolinite; rock salt
	14. Metallic minerals	Iron; copper; chromium; zinc; tin; gold; platinum
	15. Construction minerals	Stone; aggregate; limestone; brick clay; gypsum; bitumen
	16. Gemstones	Diamonds; sapphires; emerald; onyx; agate
	17. Fossils	Tyrannosaurus “Sue”: fossil and mineral shops
	18. Soil	Food production; wine; timber; fibre
Functional value	19. Platforms	Building and infrastructure construction
	20. Storage & recycling	Carbon in soil & peat; oil & gas in traps; hydrological cycle
	21. Health	Nutrients & minerals; therapeutic landscapes
	22. Burial	Human burial; landfill sites; underground nuclear chambers
	23. Pollution control	Soil & rock as a water filter; landform screens
	24. Water chemistry	Mineral water; whisky
	25. Soil functions	Agriculture; viticulture; forestry
	26. Geosystem functions	Continued operation of fluvial, coastal, aeolian processes
	27. Ecosystem functions	Biodiversity
Research & education value	28. Scientific discovery	Geoprocesses; geotechnological; geoforensics
	29. Earth history	Evolution; geological history of earth; geoarcheology
	30. History of research	Early identification of unconformities; igneous activity, etc
	31. Environmental monitoring	Ice cores; sea-level change; pollution monitoring
	32. Education & training	Field studies; professional training

Figure 13. Illustration of diversity of potentially competing Environmental Values (Reproduced from Reser and Bentrupperbäumer, 2005)

Reser and Bentrupperbäumer (2005) observe that Environmental Values have proved more complex over the years to define. This is illustrated by the table from their review reproduced in Figure 13.

Nevertheless the concept is still valuable. As of November 2016 the Environmental Values was widely used in the Australian approach to environmental resource utilization and protection (e.g. Australian Government Department of Energy and Environment, 2016 (accessed Nov)-c, Australian Government Department of Energy and Environment, 2016 (accessed Nov)-b, Australian Government Department of Energy and Environment, 2016 (accessed Nov)-a), http://www.environment.gov.au/node/14374 .

And in the national strategy for Ecologically Sustainable Development (Australian Government Department of Energy and Environment, 2016 (accessed Nov)-a) it is stated that:

ñGovernments will promote incentive structures that are capable of better accommodating Environmental Values, and will work to ensure that resource allocation mechanisms and ESD-related decision making processes are accessible, transparent, predictable and timely.ò

ANZECC and ARMCANZ (2000) provides a model case study for how ôEnvironmental Valuesôcan capture the aims of guidelines, what they mean operationally, and where they fit within biosolids guidelines. Their definition/clarification is so central that they are specified as being the first step in developing long-term management (p 2-1) along with ómanagement goalsôand level of protection including generic guideline ones. The concept is subsequently used many times in the introductory chapters of these guidelines. Of particular note in the case of NSW is that as part of their development:

ñNew South Wales (undertook)ð A six month public consultation program in 1998 identified **interim Environmental Values** and objectives for various catchments in the State. The process involved written submissions, and information and discussion forums located in central and regional locations.ò

Similarly:

*"Victoria — State Environment Protection Policies (SEPP) for water set out the 'beneficial uses' (or **Environmental Values**) to be protected in various parts of rivers, lakes, estuaries and bays and related **Environmental Values**. The SEPP process includes a legislative requirement for a period of at least three months for submissions to be received."* (and)

*"Western Australia — In 1998, development of the proposed Environment Protection (Marine Waters) Policy involved community consultation to set the **Environmental Values** and environmental objectives of Perth's coastal waters. The process included key stakeholders, stakeholder reference groups and a two month consultation period."* Etc.

The outcome was that it proved possible to operationally define ÔEnvironmental Valuesô concisely within this particular set of guidelines (ANZECC and ARMCANZ, 2000):

"(Environmental Values) are particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and which require protection from the effects of pollution, waste discharges and deposits. They were often called 'beneficial uses' in the water quality literature but this term has lost favour because of its exploitative connotations. For this reason, the term 'Environmental Value' has been adopted by the NWQMS. The following Environmental Values are recognised in these guidelines:

- *aquatic ecosystems;*
- *primary industries (irrigation and general water uses, stock drinking water; aquaculture and human consumption of aquatic foods);*
- *recreation and aesthetics;*
- *drinking water;*
- *industrial water; and*
- *cultural and spiritual values."*

This list is only slightly amended from the previous list (ANZECC, 1992) suggesting that Environmental Values if well-constructed can be are stable in the long term.

The **bolded** introduction appears directly applicable to biosolids. More generally this example indicates that development of Environmental Values that the biosolids guidelines are aimed to support could be the first step in their operational development.

2.2.6.1. 'Environmental Values' for biosolids odour, stability and vermin

Environmental Values for biosolids are at this stage unclear but it would seem sensible to consider developing them for odour and stabilization for the guidelines bearing in mind the known and conceivable impacts. Defining Environmental Values in respect to microbial and chemical contaminant management seems likely to be straightforward as analogous aims are well developed already for water and food exposure along the lines of:

- protection of workers and communities located proximate to where biosolids are processed, transported, recycled and otherwise returned to the environment beneficially, sufficient to avoid unacceptable risk (likelihood X consequence) of infection, chemical toxicity and carcinogenicity;
- protection of ecosystems proximate to and downstream of where biosolids are processed, transported, recycled and otherwise returned to the environment sufficient to avoid unacceptable risk (likelihood X consequence) of organism infection, chemical toxicity and carcinogenicity.

Our search revealed virtually no development to date of biosolids Environmental Values. For example there was nothing in the 1994 national biosolids strategy (NRMMC, 1994).

(But this document is still of note also in that it makes clear that biosolids management comes under the national water management strategy. It follows from this that biosolids related Environmental Values should have been developed as part of but the ANZECC/ARMCANZ process seems to have overlooked this issue.)

The most relevant references we found were Keeney et al (1996) and Passuello et al. (2012). The first study may be worth considering when considering what biosolids Environmental Values would look like given its subject matter and title *"Using values in planning wastewater facilities for metropolitan Seattle"*. Unfortunately the most specific references they made were as follows:

- ñFor inconvenience, odors, noises, and visual implications, we used the measure of person-years of each impact. This measure implicitly assumes that the disruption to an individual by excess traffic, odors, noise, or visual degradation is equivalent. One could value such disruptions differently, but that would suggest a level of precision inappropriate for the quality of data that could be gathered for Wastewater 2020 Plus alternatives at this preliminary stage.ò
- ñthought of such a person as one living near a treatment facility that was routinely bothered by either noise, the traffic, or the odor of the facility over that ten-year periodò.
- ñObjective 2.1.2 Minimize Odorsò
- ñMinimize Amount of Biosolidsò

Passuello et al. (2012) in their study of land use classification for biosolids based their approach in part on achieving Environment Values. This idea was partly based on an earlier Australian study (Ticehurst et al., 2007) which had scoped the Environmental Values of coastal lake catchments. Passuello et al. (2012) looked at using Bayes Nets and Multicriteria Decision Analysis (MCDA) *"to define the suitability of agricultural areas to receive sewage sludge amendment".* They appear to identify the following Environmental Values as downstream nodes in their Bayes Nets ï (tolerable) human exposure, soil and water (quality) and groundwater (protection). However odour and stability were not substantively considered.

As will become apparent below, though odours pose a more complex challenge and hence a need to clarify Environmental Values of odour, stabilization (including pest and vermin control). A list for odours and stability might include ñairò, ñwork environmentò, ñhabitationò, ñsoilò, and ñpest minimizationò. As will be seen, criteria for acceptable and unacceptable odours have been proposed. Unfortunately there is far less consensus on what constitutes tolerable odour and thresholds and these vary somewhat even for the same individual. In part this is because there are different thresholds. In this regard recycled water experience provides something of a guide (Hurlimann and McKay, 2007, Hurlimann, 2009) and it appears possible to quantify preferences for odour.

Given that most biosolids are currently recycled in rural areas it will be essential to account for the Environmental Values of such communities. Leviston et al. (2011) provide a method for identifying these and a list of key themes. Their study specifically looks at the impact of land management practices, which is what in effect biosolids soil incorporation is. In prioritising aesthetic and cultural Environmental Value significance the touchstone proposed is Maslow's hierarchy of needs. Leviston et al. (2011) discuss how this concept provides a rationale for promoting long term sustainability in agricultural practice, using in their case study the example of minimum till practice. The ultimate ideal is seen as best practice arising not only from economic drivers but from the development of a culture of 'Land Stewardship' where farmers actively engage and innovate in day to day practice. This contrasts with biosolids management which seems (see below) to more be driven by economic considerations and possibly involve manipulation of perceptions rather than biosolids application being seen as a genuine example of ecological sustainability best practice.

[For further discussion of the hierarchy of needs its relationship to the environment see (Schofer and Hironaka, 2005, Dellström Rosenquist, 2005, Mackechnie et al., 2011, Koltko-Rivera, 2006)]

So drafting clarifying and prioritizing Environmental Values for biosolids odour and stability should be an early part of the guidelines development.

2.2.7. ISO 31010 tools, a different model for thinking about biosolids odour and stability management

A different perspective on the possible contents of odour and stability guidelines is provided by developments in generic risk assessment and management. As with other guidelines originating in the 1990s/early 2000s, generic risk management has evolved significantly (Standards Australia International, 2004, Standards Australia/Standards New Zealand, 2004b, Standards Australia/Standards New Zealand, 2004a). The earlier methods are unexceptionable and still used today. However, in 2009 new much more extensive ISO standard were released (IEC/ISO, 2009, ISO, 2009) and were rapidly adopted in Australia (Standards Australia and Standards New Zealand, 2013, Standards Australia and Standards New Zealand, 2009). These greatly expanded what is meant operationally by 'risk management'. These new guidelines include an extensive summary of, and introduction to, a wide range of tools many of which appear applicable to biosolids odour and stability management. IEC/ISO (2009 Table A2) identifies 5 distinct functions/classes of different tools.

1. Scoping tool comprising lookup and support methods (e.g. Brainstorming and Delphi);
2. Function analysis tools (e.g. HACCP);
3. Controls assessment tools (e.g. Bow tie analysis);
4. Scenario analysis tools (e.g. Fault and event tree analyses);
5. Statistical methods tools (e.g. Monte Carlo and Bayes analysis).

This classification is useful as it provides an order in which to undertake risk assessment sub-tasks. It also highlights different types of risk to consider and assess, additional to classic health risks, many of which may be particularly of interest in odour and stability management. For example the tools include many óscenario analysisô options which can be used to minimise process failures. HACCP/ERA analysis was identified earlier as an approach for understanding risks and other issues based on documenting the complete (biosolids) material cycle from sludge generation to soil incorporation. But this begs the question of how to identify the highest priority issues?

A possible starting point/screening tool is the cause/consequence matrix. An illustration of how the process works with an environmental issue (ensuring clean potable water from source to consumer) is provided by Nadebaum et al. (2004). This operations oriented document illustrates risk assessment in detail and practice and provides management case studies. It is less effective in addressing the question of how (especially concurrent or cascading) events interact and how to precisely estimate likelihood beyond the use of qualitative expert opinion based assessment. However the standard also describes several tools by which this can be achieved for example the óFault Tree Analysisô method. An illustrative case study related to water supply is provided by Lindhe et al. (2012). This case study of the complex Goteborg raw water supply illustrates:

- The sort of quantitative data needed for management ï failure rates and fault remediation rates;
- How these data are used to construct fault trees;
- How different failure modes can interact and this interaction can be quantified;
- How the FTA tree format documents and prioritizes system vulnerabilities and the most important risks/issues can be identified as a prelude to strategic remedial work.

An example of FTA analysis in the water industry is that presented by Risebro et al. (2007). This study aims to understand the cause of outbreaks based on an analysis of the causative events which range from monitoring failure to treatment failure and communication failure. The events identified could mostly apply to biosolids management.

The application to undesirable odours and stability here is self-evidently that FTA is a potential tool for assessing the vulnerabilities of the biosolids processing aimed at producing a stable product and its subsequent transport and incorporation in soil.

Promotion of this sort of assessment would seem to be an essential feature of biosolids management guidelines. However, the monitoring parameters and endpoints might not be classical forms such as levels of odour. Rather the important parameters would be the likelihood of system failure and the timing of failure remediation work (Lindhe et al., 2012). Another likely relevant scenario analysis tool described is cost benefit analysis (CBA) which provides a means of assessing biosolids disposal economics.

In addition to the 5 classes listed above the guidelines provide a second categorization option based on tool use classes. The range of tools available and this classification are outlined in a table reproduced from the Australian version of the tools (Standards Australia and Standards New Zealand, 2013) in Figure 14. The latter standard identifies 6 different application categories, shown here in likely order of use, and suggests generic application situations.

1. ŕRisk identification.
2. Risk analysis-consequence analysis.
3. Risk analysis-qualitative, semi-quantitative or quantitative likelihood estimation.
4. Risk analysis-estimating the level of risk.
5. Risk evaluation.
6. Risk analysis-assessing the effectiveness of any existing controls.ò

Self-evidently each of these assessment tasks or their analogues could be applied to odour and stability management.

Usefully, different tools are identified as strongly applicable, applicable or not applicable to each of these 6 tasks in table form (The original ISO 31010 Table A1 is sorted more along the lines of the likely order of application).

This said these tool application recommendations in Table A1 are still a ówork in progressô The version reproduced below in **Figure 14** in fact differs from its predecessor in regard to its applicability recommendations (IEC/ISO, 2009 Table A1). Further, based on WRCõs experience, even the updated Australian applicability ratings are not still completely reliable. For example Bayes Nets and Bayesian analysis is considered inapplicable to risk (or other issue) identification whereas the true situation is very different (Fenton and Neil, 2012). Further, Bayes Net specialists in the past few years have been at extreme pains to develop defensible problem scoping and subsequent validation of Bayes Net models starting with a clear definition of inputs, analysis aims etc. Indeed it appears that concern for ensuring tool use/modelling validity is more advanced in the BN literature than is evident as yet in the ISO

31000 and related standard - compare (Kragt, 2009, Pollino and Henderson, 2010, Hart et al., 2005, Pollino et al., 2007, Chen and Pollino, 2012, Marcot, 2012, Marcot et al., 2006, McCann et al., 2006).

TABLE A1

APPLICABILITY OF TOOLS USED FOR RISK ASSESSMENT

Tools and techniques	Risk identification	Control analysis	Risk analysis			Risk evaluation
			Consequence	Likelihood	Level of risk	
Bayesian analysis and Bayes nets	NA	A	A	SA	A	SA
Bow tie analysis	A	SA	A	A	A	A
Brainstorming	SA	A	NA	NA	NA	NA
Business impact analysis (BIA)	A	NA	SA	A	NA	A
Cause and effect analysis	SA	A	SA	NA	NA	NA
Cause-consequence analysis	A	A	SA	SA	A	A
Checklists	SA	A	A	NA	NA	NA
Consequence/likelihood matrix	SA	A	SA	SA	SA	A
Cost benefit analysis (CBA)	NA	A	A	NA	A	SA
Decision tree analysis	A	NA	SA	SA	SA	SA
Delphi techniques	A	A	A	A	A	A
Event tree analysis (ETA)	A	SA	SA	A	A	A
Failure mode and effects analysis (FMEA) and failure mode, effects and criticality analysis (FMECA)	SA	A	SA	SA	SA	A
Fault tree analysis (FTA)	A	A	NA	SA	A	A
F-N curves	NA	NA	A	A	SA	SA
Hazard analysis and critical control points (HACCP)	SA	SA	A	NA	NA	SA
Hazard and operability studies (HAZOP)	SA	A	SA	A	A	A
Human reliability analysis (HRA)	SA	NA	SA	SA	SA	A
Layers of protection analysis (LOPA)	A	SA	SA	A	A	NA
Markov analysis	A	A	SA	SA	NA	NA
Monte Carlo simulation	NA	A	A	SA	SA	SA
Multicriteria decision analysis (MCDA)	NA	A	NA	NA	NA	SA
Preliminary hazard Analysis (PHA)	SA	NA	A	NA	NA	NA
Risk indices	NA	A	SA	SA	SA	SA
Root cause analysis (RCA)	SA	A	NA	SA	NA	A
Scenario analysis	SA	SA	SA	A	A	A
Sneak circuit analysis (SCA)	SA	NA	NA	NA	NA	NA
Structured or semi-structured interviews	SA	SA	NA	NA	NA	NA
Structured what if techniques (SWIFT)	SA	SA	SA	SA	SA	SA
Toxicological and ecotoxicological risk assessment	SA	NA	SA	SA	SA	SA

LEGEND:
SA = Strongly applicable—common usage of tool.
A = Applicable—can be used in this context.
NA = Not applicable.

Figure 14. ISO 31010 Risk assessment and management tools identified by Standards Australia (2013)

2.2.8. HACCP application in the USA relevant to stabilization

Unsurprising given its origins in the USA (e.g. National Research Council, 1983) The US national biosolids includes sections on risk assessment applicable to chemical and microbial contaminants (National Biosolids Partnership, 2005 section 2.3).

But in addition Chapters 4 (Solids Stabilization Systems), 7 (Transportation), 8 (Agricultural application), 9 (non-agricultural uses), 10 (non-restricted distribution), 12 (Storage), 13 (Biosolids Nutrient Management/Calculating Agronomic Rate of Application), 14 (external Environmental considerations) and other incinerated related chapters, all commence with identification and lists of Critical Control Points.

Further, this document (National Biosolids Partnership, 2005 Appendix F) summarizes this information with a very extensive list of critical control points covering the full production to end use chain. This is reproduced in Figure 15.

Biosolids Value Chain	Examples of Critical Control Points
Wastewater Collection and Pretreatment	Industrial – Significant Industrial User discharges
	Commercial user discharges
Wastewater Treatment and Solids Generation	Solids screening / grit collection
	Scum blanket
	Primary treatment
	Secondary treatment
Solids Stabilization, Conditioning, and Handling	Anaerobic digestion - Temperature - Digester mixing - Detention time - "End product" meets regulatory requirements - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Aerobic digestion - Temperature - Digester mixing - Aeration requirements - "End product" meets regulatory requirements - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Chemical stabilization – Class B product - Quality of add mix of chemicals / lime - Mixture consistency - Mixture pH and temperature - Mixture detention time - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Chemical stabilization – Class A product - Quality of add mix of chemicals / lime - Mixture consistency - Mixture pH and temperature - Mixture detention time - "End product" meets regulatory requirements - Location of facility – air emissions management - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Composting - Quality of add mix of bulking agent - Mixture consistency - Mixture temperature - Mixture turning - Mixture detention time - "End product" meets regulatory requirements - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
Solids Stabilization, Conditioning and Handling (continued)	Air drying system - Location of facility - Mixture turning - Mixture temperature - Mixture detention time - "End product" meets regulatory requirements - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Thermal drying systems - Location of facility – air emission management - Temperature - Detention time - Stack emissions - "End product" meets regulatory requirements - Storage bin / silo - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Bioenergy / Incineration - Thickening - Dewatering - Scum conditioning - Thickened solids holding tank - Burn zone - Scrubber - Stack emissions - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Dewatering - Location of facility - "End product" meets specifications / percent solids
	Thickening - Location of facility - "End product" meets specifications / percent solids
Solids Storage and Transportation	Solids storage - Site location - Distance to neighbors - Road access - Set back from surface water - Depth to groundwater - Any regulatory/ permit requirements that identify specific locations/activities that need to be managed
	Solids transportation - Truck (e.g., maintenance, appearance) - Truck cover - Transportation route - Truck cleaning facilities - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
Biosolids End Use or Disposal	Land application - Application site location - Location of off loading from trucks - Interim storage/staging area - Perimeter of biosolids application site-setback distances from surface water/neighbors/wells - Depth to groundwater - Agronomic rate - Truck cleaning on site - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Class A/EQ product sale and distribution - Product and packaging specifications - Product application rates - Product transportation - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Landfill - Landfill - Any regulatory/permit requirements that identify specific locations/activities that need to be managed
	Surface disposal - Site location - Perimeter of application site – setback from surface water/neighbors/wells - Depth to groundwater - Truck cleaning site - Access road - Any regulatory/permit requirements that identify specific locations/activities that need to be managed

Figure 15. Examples of biosolids management train critical control point (National Biosolids Partnership, 2005 reproduced from Appendix F)

2.2.9. Conclusions regarding applicability of risk based frameworks to odour and stability

Based on WRCô s experience, our consideration of risk assessment tools and internal discussions it appears that:

1. Harmonization of odour and stability management with these wider risk guidelines and methods is feasible and makes sense institutionally.
2. Biosolids management is closely associated with wastewater management and has been viewed nationally as falling under water management generally. So having a system harmonized with the latter was a logical option to consider.
3. What seems missing with odour and stability management in the 1997 guidelines, which a switch to risk based management could address, is:
   a. higher levels strategic perspective that modern risk management methods, which it is suggested development of Environmental Values for odour and stability could provide (In addition the application of Environmental Management Systems standards seem desirable. This is discussed in the Appendix following this one.);
   b. a holistic perspective analogous to the catchment to consumer and field to fork concepts i.e. HACCP style system analysis and exposure assessment for major exposure scenarios (as explained in the next sections it is suggested HACCP and ERA could provide this for understanding nominally functioning biosolids management systems while other risk management tools such as FTA could provide holistic pictures of system failures and malfunctions);
4. It is likely that the chemical and microbiological biosolids guideline upgrades will be based on adaptation of risk assessment and management methods.
5. The constraints and lessons from water recycling identified by the industry could be transferred to biosolids e.g. overcoming cost issues, standardization of validation across Australia from state to state.

While much in analogous environmental and risk management guidelines seems transferable, two features of biosolids management that may demand a nuanced adaptation are:

- The question of to what extent odour can be viewed and treated as a risk?
- How biosolids óstabilityô should be viewed, measured and managed?

A further matter touched on is the matter of vermin and vector management with overlaps with microbial pathogen management.

The next section explores what sort of adaptation is possible based on consideration of how odour (mainly) management can or might fit into an HACCP or enHealth risk assessment and management framework (EnHealth Council, 2012b). The following section then looks at stability and vermin/vector management.

2.3. Odour management based on the enHealth model ERA model?

2.3.1. Adapting ERA

Each of the guidelines above provides a potential model for grouping and analysing odour and stability literature as well as a model for eventual guideline development.

Given the similarities in behaviour of odours to toxic gases the enHealth Health Risk Assessment framework (EnHealth Council, 2012b, Department of Health and Aging, 2002) was viewed a best able to provide the basis for key headings for reviewing what is known about odour assessment and where adaptation would be most needed and useful. Accordingly this section of the review uses the primary ERA heads of consideration i.e.:

- Engagement with stakeholders;
- Issues Identification;
- Hazard Identification;
- Dose response assessment;
- Exposure assessment covering;
    - Odour locations;
    - Exposed populations;
    - Exposure concentration and intake;
    - Exposure pathway;
- Risk characterization;
- Risk management;
- Uncertainty assessment and reality checks.

It concludes with comments on analytical and assessment methods and where adaptation of human health risk assessment methods to odour assessment needs most attention.

Specific reasons for selecting ERA based heads of consideration are:

- The microbial and chemical risk assessment portions are likely to adopt an ERA approach. This is suggested by for example the USEPA model for pathogens (U.S. Environmental Protection Agency and U.S. Department of Agriculture, 2012).
- ERA/HACCP is the essentially the model for assessment promoted by the NBP (National Biosolids Partnership, 2005).
- To some degree there is overlap with chemical risk assessment as many odourants are toxic in high quantities.
- EnHealth have flagged including odour assessment in this scheme, though as yet no final decision has been made.

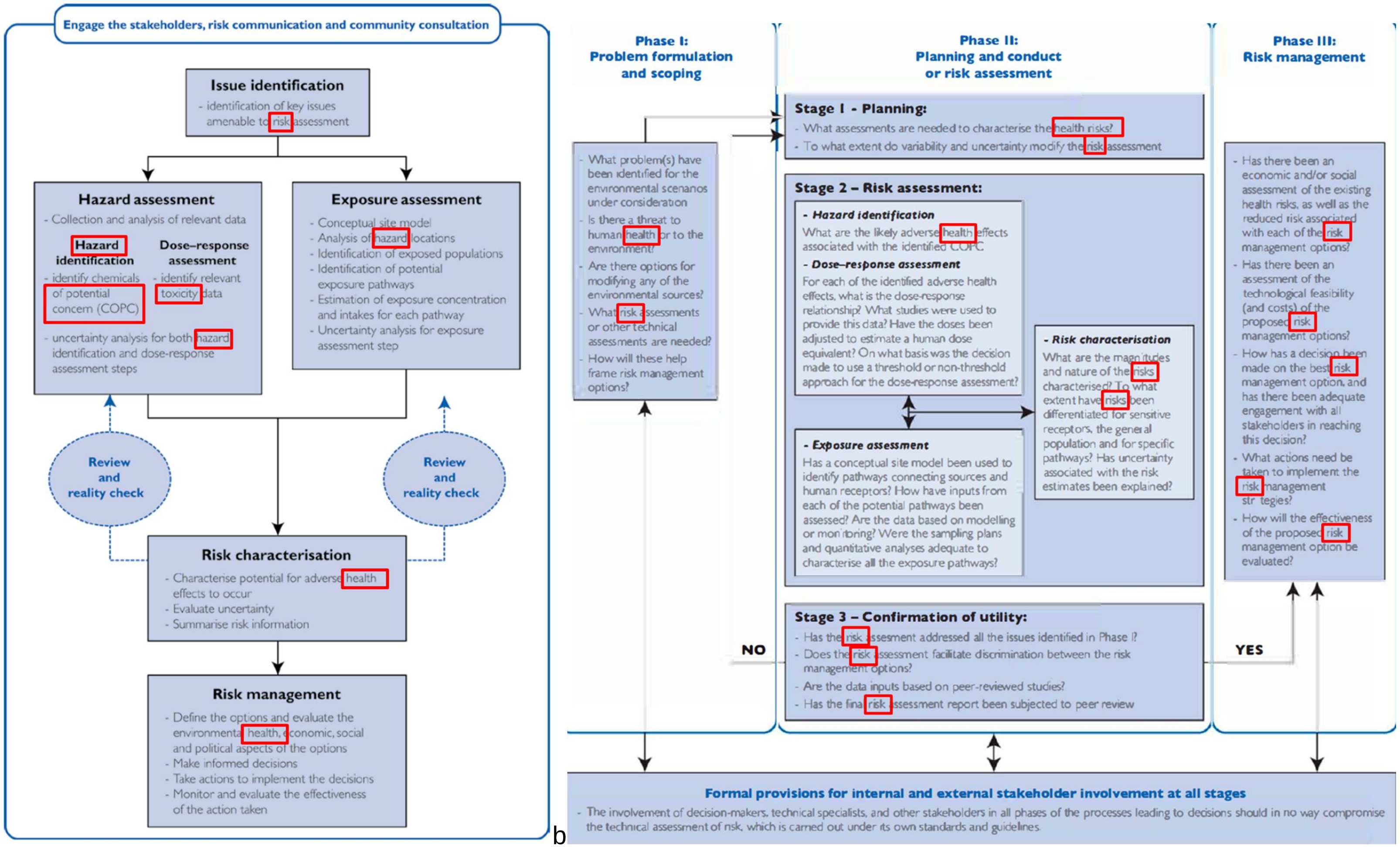
- EnHealth Exposure Assessment is essentially the same as HACCP and provides a straightforward framework for linking emissions with distant impacts.
- ERA activity categories are neither excessive nor too limited in number.
- Management flows as a natural outcome of nuisance characterization.
- The enHealth scheme is known to be accepted by NSW Health.
- In WRC's experience the framework is easily understood by, and explainable to, stakeholders in terms of cause and effect.

EnHealth's key features are captured in its primary system analysis framework summarized Figure 1 and 2 of the guidelines (EnHealth Council, 2012b). For information these are reproduced in Figure 16 below.

The main points for adaptation are identified in red boxes and primarily relate to the extent odours can be viewed as risks or hazards. As noted above the ISO definition of risk is sufficiently generic that 'risk' can be kept provided it stakeholders can appreciate that the concept of 'risk' does not equate to a health risk *per se*. The concept of 'Chemicals of Potential Concern' similarly seems possible to retain providing it is understood that concerns can be ones as well as ones derived from easily verified physiological ones e.g. toxicity in experimental animals.

This leaves the concepts of Hazard, Toxicity and Health in need of adaptation for the ERA scheme to be applicable. How this might be done is suggested in Section 2.3.11 based on the intervening literature and considerations reviewed as well as the previous parts of this review.

The concept of biosolids 'Stability' appears to fit into the scheme in a different way to odours. How it might be dealt with is discussed in Section 2.4.



a. b

Figure 16. Enhealth ERA framework showing points where modification of concepts and language for odours is needed

a. Primary enHealth HRA(ERA) framework

b. Sequence of implementation steps

2.3.2. Engagement with stakeholders/risk communication/consultation

The preparation this review did not involve any engagement with stakeholders. However this and its complementary reviews should provide the starting information from which such consultation with primary stakeholder should proceed. In undertaking such consultation EPA probably need to recognise there are at least four distinct stakeholder groups that need to be consulted on odours:

- the industry and prospective regulators including biosolids workers, private auditors and local government health surveyors and engineers who in NSW together with the NSW Department of Commerce have custodianship of sewage treatment plants and sludge management;
- farmers where land application is proposed and who need to be fully informed on how sustainable and beneficial long-term biosolids application is likely to be on their specific land[11];
- (odour) sensitive populations;
- the public in the vicinity of areas impacted by biosolids especially those from where complaints have originated in the past.

A model for consultation may be that undertaken when the ANZECC/ARMCANZ (2000) guidelines were developed. This wide consultation was necessitated by many especially rural communities similarly being directly impacted by water management and availability. A model for engagement on the topic of biosolids is provided by Beuth Verlag GmbH (1997). Other examples of how stakeholders especially the community might be consulted are found in the scientific literature e.g. (La et al., 2011, Yu and Guo, 2011)

Hayes et al. (2015, 2014a) provide an up to date review of considerations for project stakeholders especially proponents and regulators who would need to communicate a range of at times quite technical concepts. **It could be very useful for the new guidelines to capture such information concisely for general circulation in a format comparable to the diverse factsheets for drinking water (NH&MRC, 2013) provided in these guidelines.**

2.3.3. Issue identification - Outcome of WRC group scoping

Beyond the primary focus of this review, biosolids odour management, there are a range of issues which each of this review's authors identified. From discussions within our group the following were major considerations in respect to odours which could be included in such a

[11] A concern during the development of ANZECC/ARMCANZ (2000) guidelines was that water bodies vary in sensitivity and 'assimilative capacity'. This is covered to a degree in the 1997 guidelines. But it is unclear to what extent the farmers accepting biosolids have been appropriately supported and what hazardous events have occurred which would lead to unacceptable odour generation.

check list (further check items are identifiable/designated also with capitalized Roman numerals):

I. Annoyance/Nuisance/risk from odours to exposed populations
II. The focal HACCP pathway is
    a. Sludge >
    b. satisfactorily stabilized biosolids >
    c. low odour emission material suitable for storage and transport>
    d. limited transport of odours from source including after soil incorporation >
    e. limited impact on community
III. There are other implications of evidence from unacceptable odours especially that their processing, transport, incorporation and/or storage are also failing in respect to microbial and chemical risk reduction.
IV. Worker OH&S needs special consideration especially where biosolids are enclosed to control odour emissions.
V. Vermin (flies, midges and rodents - spiders) control is insufficiently understood at this point in time for credible management scheme development (note that it may be a concern or the risk posed by vermin may be trivial).
VI. Analysis of biosolids management problems appears to have been insufficiently holistic in the past e.g. only looking post collection from primary owner or at the odour generation location.

The guidelines would probably need to develop a still fuller list of these. Checklists are also already well developed within the current guidelines (NSW EPA, 1997) and are unexceptionable and should be incorporated as well. Nevertheless these should probably be revisited for example during a consultation phase.

In line with a HACCP style analysis odour issues should be considered across the full production and 'beneficial reuse'/disposal chain e.g. where do the emissions on site, at first production and extraction from ASP and other sludge generators fit into this?

As noted previously, water and food management use the short-hand vernacular expressions "catchment to consumer", "source to tap", and "field to fork". Accordingly it is suggested that a similar shorthand be developed to describe the over biosolids not as a form of greenwash but to remind the stakeholders to look at biosolids management holistically e.g. :

- "Sludge to soil"
- "Solid waste to soil conditioner"
- "Biosolids to biomass"
- "Organic waste to organic soil conditioner"

2.3.4. Hazard Assessment - Odour as a hazard as a source of risk?

The extent to which odour is, or should be seen/treated as, a risk, is a key question for NSW EPA to resolve. NSW EPA already promotes the application of risk assessment in principle [see quotes above in (Department of environment and Conservation (NSW), 2005, Department of Environment and Conservation (NSW), 2006a, Department of Environment and Conservation (NSW), 2006b)]. In addition it promotes use of quantitative pollutant exposure via assessment methods such as air pollutant transport modelling. WRC suggests this question remains to be answered and in addressing it the following should be considered.

2.3.4.1. Australian 31010 risk management standard

Past concerns in respect to risk have tended to focus on damage to human health e.g. toxicology or damage to the environment. But the newer general standards (Standards Australia and Standards New Zealand, 2009, Standards Australia, 2012) effectively expand the concept of risk so that odour could be included as a hazard equivalent:

ñEffect of uncertainty on objectives.ò (Standards Australia and Standards New Zealand, 2013, ISO, 2009)

This broad definition of risk is not new but is also present in the previous generation of risk management documents as well (Standards Australia/Standards New Zealand, 2004b). The general nature of this definition indicates the concept of risks, and hence risk management, cover any undesirable (and even desirable) deviation from the preferred biosolid status/characteristics and so risk assessment can cover whether the following are being considered:

- Are biosolids emitting odours sufficient to pose a human or ecosystem health risk?
- Are biosolids emitting odours sufficient to be unacceptably offensive?

This is consistent with other parts of the standards. In respect to the relationship between the concept of óriskôand óhazardôit appears hazards are seen as one type of risk that needs managing. The ISO standard (IEC/ISO, 2009) states:

ñThe risk identification process includes identifying the causes and source of the risk (hazard in the context of physical harm), events, situations or circumstances which could have a material impact upon objectives and the nature of that impactò

2.3.4.2. Human health risk and offensiveness

There is now a range of literature indicating odours are not merely a trivial nuisance but cause a variety of confirmed health effects (**Table 30**). Several of these symptoms are difficult to pin down to one of the bodyôs primary physical receptors for which dose response algorithms and model assessment frameworks have been developed (i.e. skin, eye, gut, respiratory system). Nevertheless their diversity indicates the health impacts of odours need to be taken seriously when determining exposure limits for biosolids quite apart from toxicity issues.

Table 30. Reported symptoms of odour exposure[1]

Symptom	Source
Eye irritation	(Wing et al., 2008, Shusterman et al., 1991, Sucker et al., 2009, Schiffman and Williams, 2005, Neutra et al., 1991, Bullers, 2005, Dalton and Dilks, 1997)
Nose irritation	(Wing et al., 2008, Shusterman et al., 1991, Sucker et al., 2009, Schiffman and Williams, 2005, Neutra et al., 1991, Bullers, 2005, Dalton and Dilks, 1997)
Throat irritation/ coughing	(Wing et al., 2008, Shusterman et al., 1991, Sucker et al., 2009, Neutra et al., 1991, Dalton and Dilks, 1997)
Respiratory problems	(Thu et al., 1997, Sucker et al., 2009, Schiffman and Williams, 2005, Neutra et al., 1991, Wing et al., 2008, Bullers, 2005, Dalton and Dilks, 1997)
Stress increase	(Wing et al., 2008, Shusterman et al., 1991, Neutra et al., 1991, Dalton and Dilks, 1997)
Negative mood	(Wing et al., 2008, Shusterman et al., 1991, Schiffman and Williams, 2005, Neutra et al., 1991, Dalton and Dilks, 1997)
Stinging sensation	(Wing et al., 2008, Shusterman et al., 1991)
Vomiting	(Schiffman et al., 2000, Bullers, 2005, Dalton and Dilks, 1997)
Headaches	(Schiffman et al., 2000, Sucker et al., 2009, Schiffman and Williams, 2005, Wing et al., 2008, Bullers, 2005)
Nausea	(Shusterman et al., 1991, Thu et al., 1997, Schiffman and Williams, 2005, Neutra et al., 1991, Bullers, 2005)
Insomnia/difficulty sleeping	(Sucker et al., 2009, Neutra et al., 1991)
Gastrointestinal issues	(Sucker et al., 2009, Schiffman and Williams, 2005, Neutra et al., 1991, Dalton and Dilks, 1997)
Skin irritation	(Bullers, 2005)

[1]Compiled by James Hayes (2016)

Three different mechanisms are identified by Schiffman and Williams (2005) as being responsible for these effects:

- ŉFirst, symptoms can be induced by exposure to odorants (compounds with odor properties) at levels that also cause irritation or other toxicological effects. That is, irritationð rather than the odorð is the cause of the health symptoms, and odor (the sensation) simply serves as an exposure marker.
- Second, health symptoms from odorants can be due to innate (genetically coded) or learned aversions.
- Third, symptoms may be due to a co-pollutant that is part of an odorant mixture.ò

2.3.4.3. EnHealth view (EnHealth Council, 2012b)

As WRC understands enHealth is central to NSW Healthôs human health risk assessment. Overall enHealth suggests this question of whether odours should be dealt with under conventional ERA is a grey area:

ñThe issue of whether the negative impacts of odours that affect quality of life should be classified as adverse health effects is controversial. While it is undoubtedly important for these matters to be considered in a standard-setting process, it is debatable whether the appropriate place is within the scientifically rigorous steps of risk assessment outlined in this guidance document, or during the consultative processes that accompany risk management.ò

This suggests they are wary of considering psychosomatic effects as part of classic ERA which was developed with the clear human health risks posed by toxic and carcinogenic chemicals, and more recently pathogenic microorganisms, in mind. An example study of psychological effects of odours is Papo et al. (2006). That said the enHealth commentary also includes guidance on the following:

- ñhow to assess the effects of odour, including how to determine whether óobjectionable or offensive odourô is causing adverse effects;
- how to monitor the effects of odour through community surveys, odour diaries and council investigations;
- when to use dispersion modelling for odour assessment;
- how to manage odour emissions, including some basic information on suitable mitigation options;
- an odour impact assessment checklist;
- references to relevant legislative or regulatory instruments that impact on odour assessment.ò

In short, though enHealth appear wary of labelling odours an environmental health risk they still support employing environmental risk <u>style</u> assessment. Separately as indicated above the concept of risk is now seen as broader than human health risk.

2.3.4.4. DALYs

In assessing risk impacts an important relatively recent development is the rise of the Disability Adjusted Life Years (DALYs) (Pruss and Havelaar, 2001):

ña é . common measure for examining diverse disease outcomesé .(which)é .. combines years of life lost by premature mortality (YLL) with years lived with a disability (YLD), standardised by means of severity weights.ò

DALY factor are familiar to water managers as being increasingly the basis for risk benchmarking in the water industry in respect to pathogens and chemicals risk and their removal (e.g. Pruss and Havelaar, 2001 , Havelaar and Melse, 2003). However their applicability is much wider and in fact they were designed to allow comparison of all risks which might impact on human óquality of lifeô The determination process illustrated in

Stouthard et al. (1997) shows that the decision depends on ratings by clinicians and mental impacts figure very highly.

In the DALY ratings comparing all death/disability impacts, psychological conditions/responses are non-trivial and include ánxiety disordersô(Murray et al., 2012). A breakdown of different psychological disorders is provided by Whiteford et al. (2010). In the DALY scheme, mental and substance use disorders constitute 7.4% of DALYs just behind the DALY burden of cancers (7.6%). Within this group, depressive and anxiety disorders are the two most important (41% and 15% respectively). Thus it is arguable that ópsychosomaticô illness risks, including from odour exposure, need consideration.

WRC concludes that NSW EPA needs to consult closely with NSW Health and clinicians in areas where biosolids have been reused to ascertain and define odours in terms of óriskô, how to distinguish them from/align with classical health risks and the significance of psychosomatic risk.

One complication is that most current literature concerns animal odours especially those from piggeries, rather than biosolids and the impacts of even these odours are still unclear (e.g. O'Connor et al., 2010) being potentially due to association with better understood hazards such as H_2S and organic toxic dust.

2.3.4.5. Animals/ecosystem hazardous impacts

Odour and scent are central to wild and domestic animal behaviour (KATS and DILL, 1998, Brown, 1979, Apfelbach et al., 2005) . We were unable to find any studies which addressed the issue of negative animal response alone to anthropogenic odour. However interaction with waste sites is known to alter predator behaviour such as with polar bears and hyenas (Lunn and Stirling, 1985, Kolowski and Holekamp, 2008). And it is well recognized that biosolids odours can attract wild animals mainly arthropods and rodents (see below). However the question of the converse remains to be explored.

2.3.4.6. WRC group scoping of the hazard posed by odours

Our WRC group scoping focused on the challenges to objectively quantifying hazards and provisionally concluded the following:

VII. Odours cannot be generally associated with a single compound but rather mixtures such as a variety of sulphur compounds in varying concentrations which tend when first detected to be well below toxic levels even if they are unpleasant;

VIII. Adverse odours can also be the result of different combinations whose interactions>result are hard as yet to quantify;

IX. Odour óhazardô potential and adverse reactions will likely be a function of emission duration X Emission óconcentrationô X Exposure duration X Hedonics [land use type, experience of annoyance class, quality of life (Swinton et al., 2007, Peters et al., 2014a)], and location;

X. Intensity as odour (OD units) value will reflect various non-parametric algorithms, odour concentration, and person to person variance;

XI. A separate concern is risks associated with odour concentrations immediately prior to dispersal to which site workers are exposed. Such workers may tolerate higher than safe exposure which their odour senses would otherwise alert them to avoid (e.g. Persaud, 2016). Reasons for ignoring such warnings include work pressures. In addition there seems to be an attitude in rural areas that risks ógo with the territoryô This attitude is reflected in for example high tractor injury and death rates.

2.3.5. Dose response

2.3.5.1. Understanding odour dose response

Dose response is still an active area of research. Taking microbial dose response as a model, early framing of the problem proposed the idea of a single number ï in this case the Minimum Infection Dose (Magnússon et al., 2012). Subsequently reflecting chemical toxicology experience, probabilistic methods were introduced (e.g. Holcomb et al., 1999). This improvement together with exposure assessment led to the roll out of holistic QMRA which is essentially ERA applied to pathogens discussed above (U.S. Environmental Protection Agency and U.S. Department of Agriculture, 2012) . Unfortunately this use of algorithms can obscure the fact that these relationships are still empirical and do not clarify how pathogenicity operates in the body. An illustration of the complexity of the latter process can be seen in this review of pathogenic *Escherichia coli* (Kaper et al., 2004).

The need for a more sophisticated understanding of odour dose response is illustrated by the complex of possible responses listed in **Table 30** which imply a range of pathways and hence mechanisms. And beyond these are the mechanisms driving the social dimension of odour response.

This challenge of better understanding response physiology is now conceptually addressed via the Key Events Doseï Response Framework: a cross-disciplinary mode-of-action based approach to examining doseï response and thresholds or KEDRF (Julien et al., 2009, Buchanan et al., 2009). This approach is exemplified by Brüning et al. (2014). However it is still very early days in the development of full KEDRF frameworks. This is illustrated by the only microbial mechanism based dose response relationship/model we are aware of being that of Rose and Haas (1999).

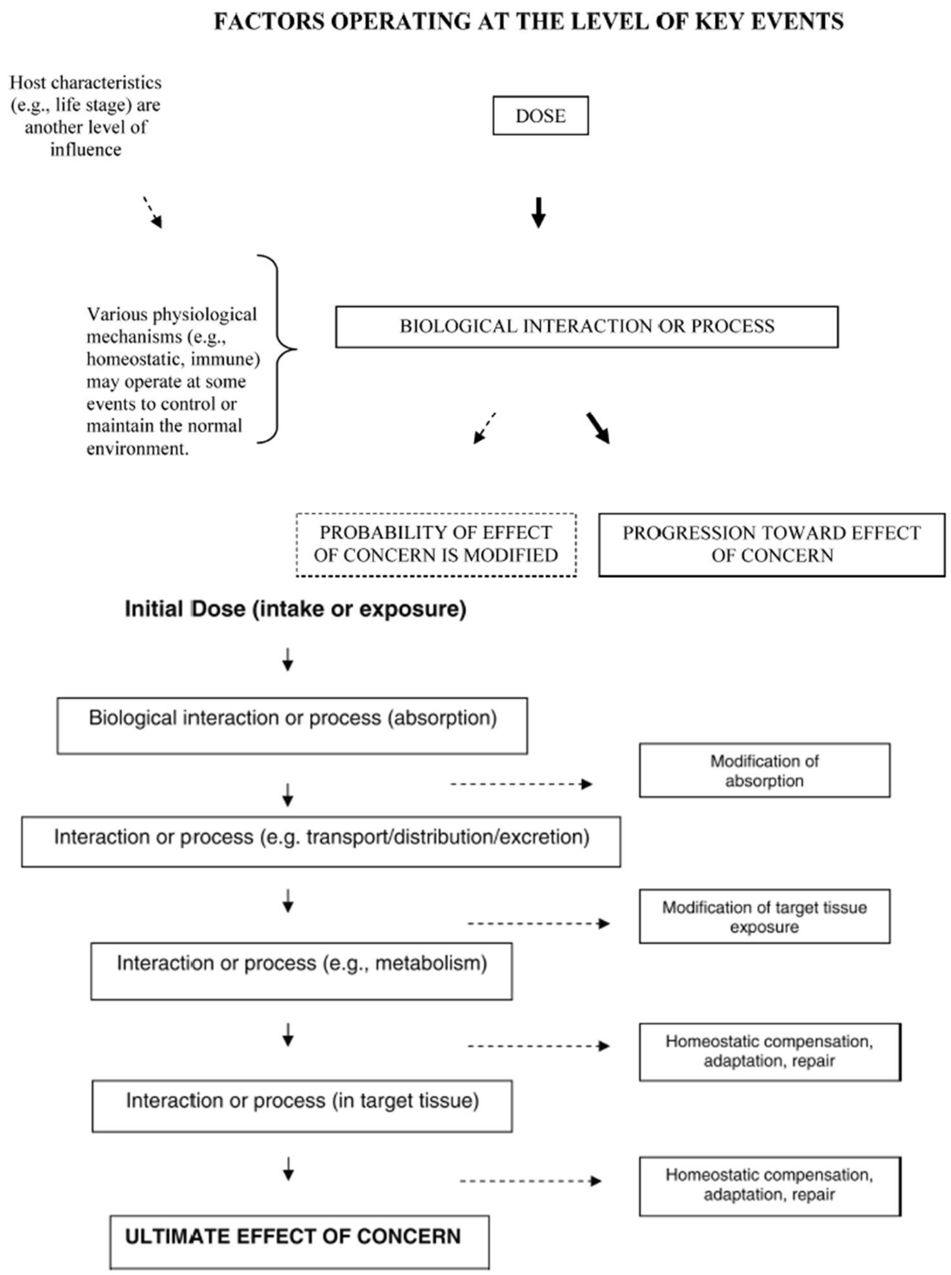


Figure 17. Elements of the KEDRF framework (reproduced from Julien et al., 2009)

So the lack of such formulations of odour dose response is unsurprising. That said:

- As with microbial dose response, empirical probabilistic relationships are now widely available for many odours as described below;
- Qualitative analysis of responses is also useful.

Table 31 outlines in order of severity, levels of response reflecting the increasingly sophisticated analysis in the odour science field. Levels 6) somatic irritant, 7) chronic toxicity, and 8) acute toxicity are clearly issues which conventional ERA is directly applicable to, most likely at points of high exposure for biosolids workers. Levels 1) and 2) odour detection and recognition appear to pose no problem necessarily. Thus the focus of odour management should focus dose responses 3) odour annoyance, 4) odour intolerance and 5) perceived irritant.

Table 31.Odour impact scheme reproduced from Schiffman et al. (2000)

Level	Description
1) odour detection	The level of odour that can first be differentiated from ambient air.
2) odour recognition	The level of odour at which the odour quality can be characterized, e.g., the level at which a person can detect that an odour is apple or manure.
3) odour annoyance	The level at which a person is annoyed by an odour but does not show or perceive a physical reaction. Note: Health symptoms are not expected at these first three levels unless the odour occurs with a co-pollutant such as dust as in Paradigm 3 or the level of annoyance is intense or prolonged.
4) odour intolerance	The level at which an individual may show or perceive physical (causing somatic (somatic) symptoms to an odour. symptoms) Note: This level corresponds to Paradigm 2 in which the odour induces symptoms even though the odourant concentration is lower than that known to cause irritation.
5) perceived irritant	The level at which a person reports irritation or physical symptoms as a result of stimulation of nerve endings in the respiratory tract.
6) somatic irritant	The level at which an odourant (not an odour) results in a negative physical reaction regardless of an individualǿs predisposition. This can occur when an odourous compound (e.g., chlorine) damages tissue. Note: Perceived and somatic irritation correspond to Paradigm 1.
7) chronic toxicity	The level at which an odourant can result in a long-term health impact.
8) acute toxicity	The level at which an immediate toxic impact is experienced, e.g., a single event may evoke an acute health impact. Note: In the case of chronic or acute toxicity, the compound should not be considered an odourant but rather a compound with toxic effects that happens to have an odour.

2.3.5.2. Odours as indicators of irritation

When considering the dose response to odours, a complicating consideration is that odour may alternatively be viewed as an indicator of a hazard as well as a hazard itself. The use of indicators is well developed and known in other environmental assessment fields such as microbial risk assessment where enteric bacterial indicators have been part of normal practice for over 100 years including assessment of biosolids safety. In their most recent formulations some indicators may have even been used to directly estimate risk using an empirical dose response curve (e.g. Kay et al., 2004, Kay et al., 1994). Conversely bacteria classically viewed as indicators can also be pathogenic as with pathogenic *E. coli* (Kaper et al., 2004).

A comparable situation exists with odour. Paustenbach and Gaffney (2006) discuss the relationship between risk, risk perception and odour and summarise it in terms of three conceptual models:

- ñModel I represents potent chemicals that may cause irritation at levels below which their odor can be detected.
- Model II represents chemicals that have an odor threshold below the irritation threshold.

- Model III describes odorous chemicals that have detectable odors at concentration levels several orders of magnitude below the levels at which they are irritants.ò

Beyond this uncertain/variable relationship between odour perception, risk perception and actual risk, there are the following secondary complications in this risk indicator system:

- ñThe source or odor is not of perceived benefit to the observer;
- The source or odor is not under the control of the observer;
- The source or odor is considered an exotic or unfamiliar technology;
- The source or odor has perceived risks that are dreaded (e.g., cancer, birth defects) or are potentially catastrophic;
- The odor reminds the observer of some prior unfortunate event (e.g., such as hydrogen sulfide exposure and nausea);
- The exposure is environmental in nature and may be perceived by the observer to threaten his/her family and neighbors as well as his/herself.ò

From this it appears odour responses may be viewed like chemical and microbial indicator systems except that they are inbuilt to most people. Like laboratory analysis based indicator systems they are both invaluable and imperfect. Thus it is important to recognize in managing odour exposure that adverse responses are a protective even if they are objectively imperfect sense and a natural hazard measuring device that must not be compromised by dismissing complaints of bad odour as trivial.

To what extent Biosolids odour detection should be seen as a reliable indicator of problems probably needs clarification in the guidelines. Biosolids odours have a clear protective function if the indicate inadequately treated/stabilized biosolids.

2.3.5.3. Empirical odour dose response algorithms

Odour responses have proved to follow sigmoidal dose responses analogous to those seen with chemicals and microorganisms (e.g. Holcomb et al., 1999). There are now many examples (Nicell and Henshaw, 2007, Nicell and Henshaw, 2006, Nicell, 1994, Nicell, 2003, Nicell, 2009). Which alternative function (e.g. exponential, logistic, beta Poisson) provides the best fit is unclear at this point but probably not critical for the purposes of biosolids management guideline development. Usefully it appears that:

- Odour dose response algorithms can be used in much the same way as those for pathogens and toxic chemicals;
- While the probability of annoyance, discrimination, detection and complaint may follow somewhat different curves, the curve shapes are relatively comparable;

It is the opinion of some that Odour Units (OU) tend to be inconsistent and incompletely reliable. However the same can be said of chemical and especially microbial dose response algorithms where the 50th percentile response may range over several magnitudes. Thus the question to ask may be how useful as a decision support odour unit measurement is or can be for various purposes e.g. for detection of a malfunctioning process. Regulation is not the only risk management purpose to which these OU measurements may be put.

Illustrative curves are reproduced in Figure 18 and Figure 19. It appears that for most measures, the human population generally tends to be similarly distributed in respect to percentiles. For example Figure 20 suggests that the lower 5th percentile and upper 95th percentile of odour detection likelihood lie within ± 1 order of magnitude of the median odour threshold. If this proves the case with biosolids this suggests a model population sample could be sufficient to provide the data for estimate the likelihood of complaint and annoyance in quantitative form.

A complication with biosolids is that different stabilisation processes will likely yield different odour compounds as will process failure or malfunction. This in turn may increase the diversity of algorithms the guidelines might document/recommend for industry use.

The guidelines ideally would include appropriate dose response algorithms where available.

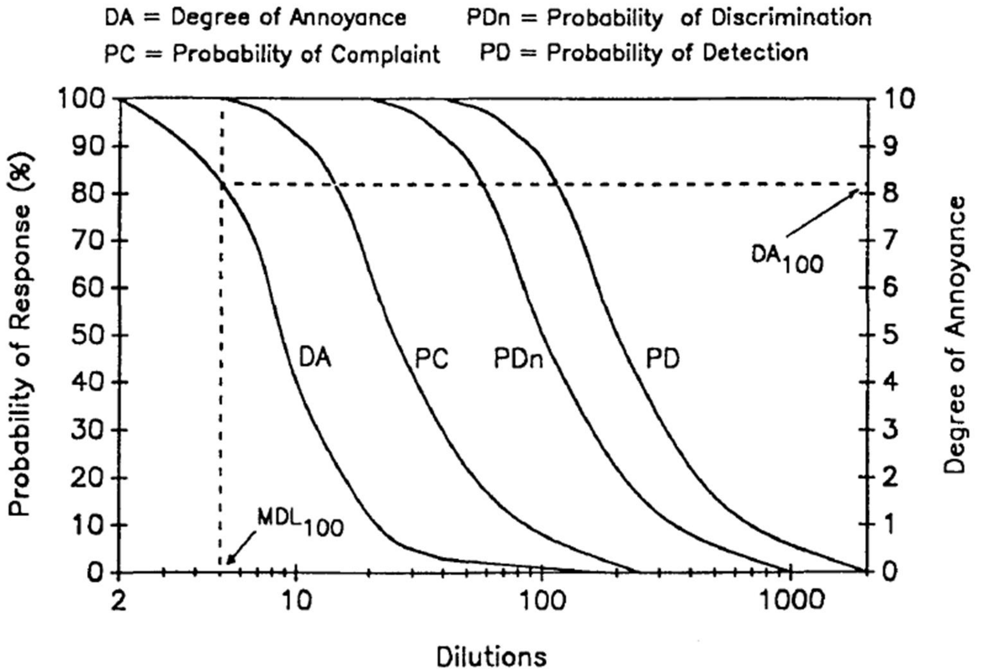


Figure 18. Idealized odour dose response model (Reproduced from Nicell, 1994)

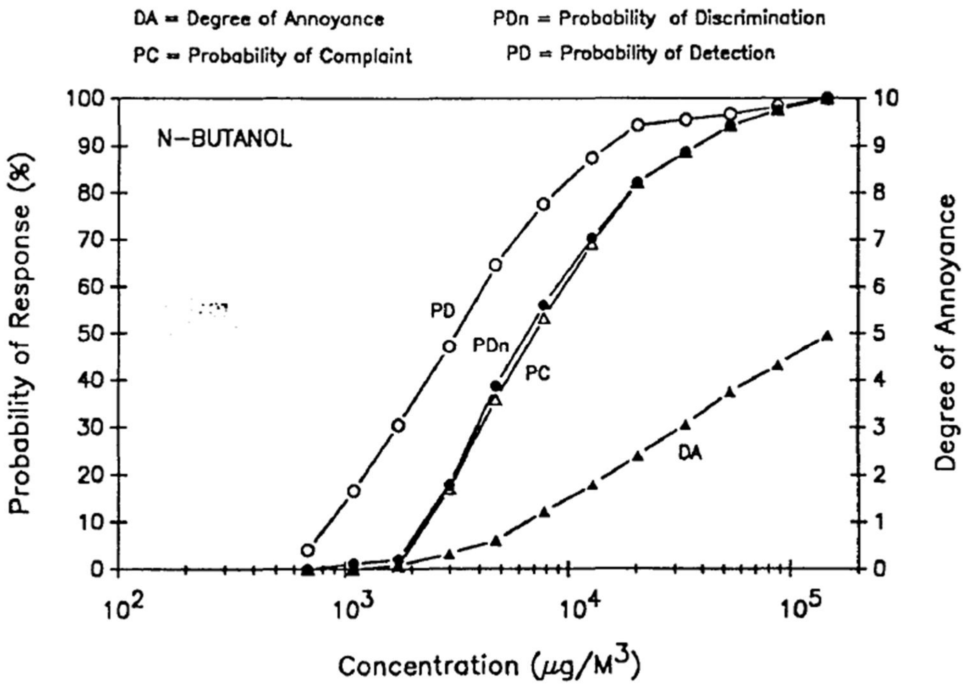


Figure 19. Butanol model (Reproduced from Nicell, 1994)

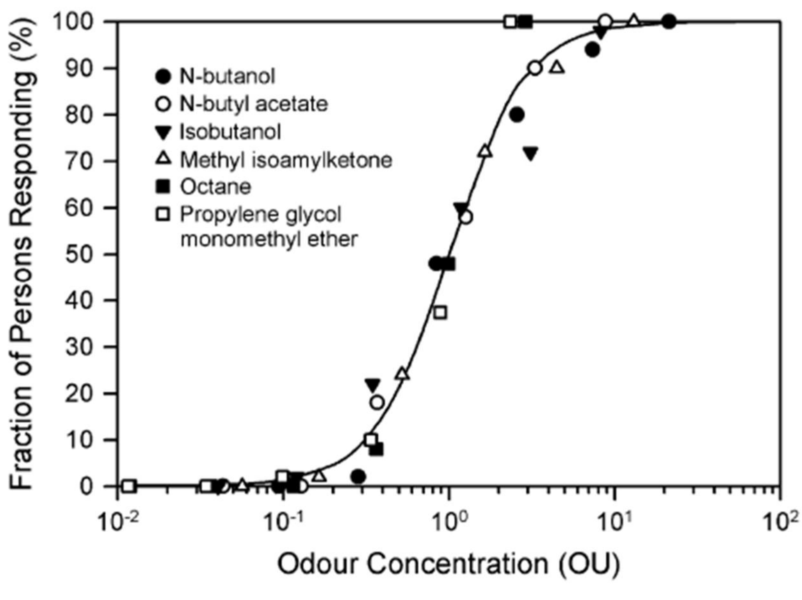


Figure 20. Consistency of the dose response relationship across different odorants (Reproduced from Nicell, 1994)

2.3.5.4. Dependency of dose response on odour type and 'pleasantness'

A complicating consideration in developing or identifying odour dose response algorithms is the setting of the unpleasantness threshold. Different odours vary greatly in their 'pleasantness' and this will affect the point at which they are rejected by the responding stakeholder population. Depending on the odour source annoyance levels can be comparable to detection levels (unpleasant odours) or very different (pleasant odours) as shown in Figure 21 (Miedema et al., 2000).

Biosolids annoyance has not been detailed. But this study indicates that:

- the % of highly annoyed individuals reflects the measured odour concentration quantifiably; and
- that for an extreme organic waste comparable to biosolids (pig farm, rendering plant) the fifth percentile of high annoyance is in the region of 1 to 5 odour units (98th percentile of the odour exposure concentrations).

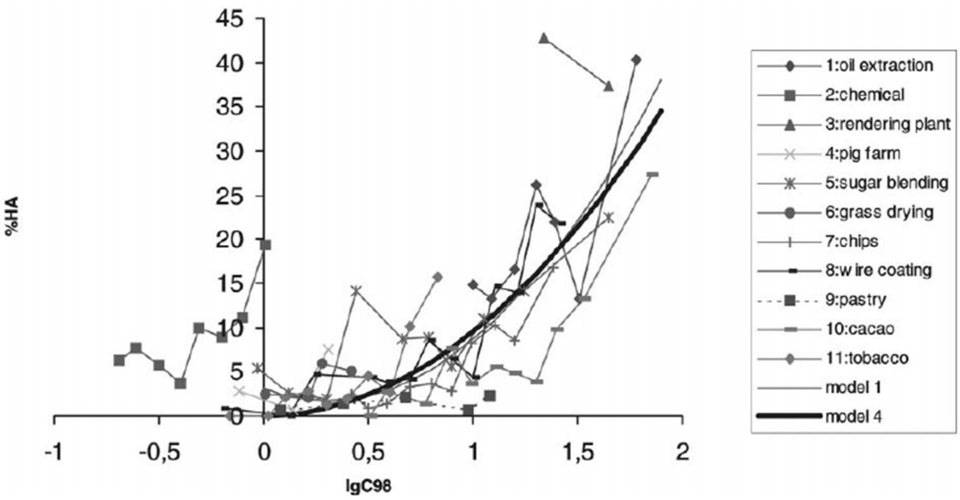


Figure 21. Percentage highly annoyed (%HA) as a function of the logarithm of the 98 percentile of measured odour concentrations (Reproduced from Miedema et al., 2000)

2.3.5.5. Positively perceiving biosolids?

Just as unpleasant odours are able to induce negative (dose) responses (e.g. Papo et al., 2006), so appealing odours can have the reverse effect. A positive response to odour can be induced not just directly by a pleasant odour such as a perfume. It can be induced by visual cues (Magnini and Karande, 2010, Ghosh and Sarkar, 2016) (Fenko et al., 2014), sounds (Davis et al., 2013, Davis, 2010) and even touch (haptic) (Ghosh and Sarkar, 2016) which are associated with pleasant odours.

This behaviour is of interest to advertising and tourism as if offers marketing opportunities (Magnini and Karande, 2010). It also highlights how important odour is to perceptions of whether a place or situation is good/safe/desirable generally and how human senses and decisions about the world interact. Conversely it implies there are financial risk/costs which could arise for a locality where it is known or perceived that large scale application of biosolids is taking place, even if these biosolids have been stabilised as far as practicable.

We did not identify any surveys of human perception based response of odours specifically arising from recycling of biosolids. However, responses to recycling of a related product of water treatment, recycled water, have been documented in Australia and provide a model for understanding perception responses to sewage wastes. For example despite its much higher degree of treatment and management recycled water is perceived to have a significantly reduced value for several purposes compared to normal potable water (Hurlimann, 2009, Hurlimann and McKay, 2007). What this work seemed to show is that where the use of hazardous material is contemplated the preference is for there to be no odour at all as one reality check on safety.

A review of perceptions and recycled water is provided by Dolnicar et al. (2011) whose potentially relevant observations include:

"(2) positive perceptions of, and knowledge about, the respective water source are key drivers for the stated (public) likelihood of usage; and

(3) awareness of water scarcity, as well as prior experience with using water from alternative sources, increases the stated likelihood of use."

These extracts suggest sympathy for recycling depends on awareness of the need for recycling wastes. Reflecting this they conclude:

"1. It is essential that people understand that water from alternative sources is not an option, but a necessity; and

2. Suggesting non-threatening ways for people to be able to experience recycled and desalinated water may be a useful strategy to increase public acceptance and usage.

Nonthreatening ways include voluntary opportunities, such as tasting recycled and desalinated water, filling public swimming pools with recycled and desalinated water. These techniques are likely to be far more effective than public announcements stating that recycled or desalinated water would be added to water supplied to households."

This analogy suggests that the public engagement as promoted by the enHealth ERA model (EnHealth Council, 2012b) and education need to be included in biosolids odour management options. Further, the concepts underpinning biosolids reuse and how odours are being managed, need to be explained to stakeholders. **In this regard it is notable that the current interim guidelines (NSW EPA, 1997) contained little on appropriate communication with the public. So public engagement is clearly a gap the guidelines need to address.**

2.3.5.6. Dose response - group scoping of issues

Our group scoping of dose response issues identified the following considerations/issues which might be covered by the guidelines.

XII. Consistent with the literature, odour appears able to induce health effects ï sinonasal irritancy and dizziness, general toxicity at high concentrations, lethargy, poor sleeping, irritability, depression;

XIII. At lower odour levels where psychosomatic effects occur it is hard to determine what and what are not seeming irrelevancies e.g. toothache;

XIV. Trigeminal nerve activation (itchy/sneezy nose) was seen as one annoyance factor.

XV. The place of Asthma triggering was unclear. Vernon et al. (2012) classified triggers as follows:

   a. Allergic triggers notably Pet dander, Dust mites, Pollens, Molds
   b. Physical triggers notably allergic rhinitis and exercise
   c. Environmental triggers notable - Air pollutants, Tobacco smoke, Humidity and Cold air

The question this raises is how far minor odours may affect Asthma occurrence. Johansson et al. (2010) reported that 6% of their study group appeared to have airway sensory hyperactivity and this could be associated with asthma. Mirabelli et al. (2006) reported increased asthma close to high odour generating pig farms. Together these suggest asthma may be a concern though at present the main trigger of concern seems to be aerosolized endotoxin[12] (Brooks et al., 2006).

XVI. In a general review of odours and community response Hayes et al. (2014a) noted the often poor correlation between odorant and odour concentration and annoyance summarized as follows:

"As suggested by Winneke et al. (1996), the assessment of psychological factors improves our understanding of why correlations of odour concentration and reaction to that odour are low, yet the actual concentrations of these odours still require attention. While cognitive appraisal plays a crucial role in the assessment of annoyance for community members, the relationship between variations in odour concentration and community awareness is at times noticeable or very strong when combined methodologies are implemented. (<u>Hence the need for clear dose response relationships</u>)."

Concern was expressed about the large uncertainties associated with odour dose response curves. While this is important to recognise, in fact, as flagged above, the issue of

[12] Endotoxin impacts is a major concern for concentrated animal feeding operations (CAFOs). It is unclear whether endotoxins should fall best under chemical microbiological or odour risk assessment. But the issue should still be flagged.

uncertainty applies similarly to chemical and microbial dose response. In the case of chemicals such models are often based on animal response which may be different to that of humans. In pathogen dose responses curve fitting is often limited by data paucity and its origin in diverse strains. This results in these dose responses also having high uncertainty (e.g. Figures in Teunis et al., 2008b, Teunis et al., 2008a). But this has not limited their value operationally as quantitative methods allow the basis of risk calculations to be clearly defined.

XVII. Better definition of threshold levels needs to be undertaken e.g. to distinguish odour identification from odour detection levels.

2.3.6. Exposure assessment

Linking hazards to dose response requires exposure assessment. This will be specific to each biosolids processing operation and subsequent storage, fate and transport. Some pathway models of biosolids exposure pathways are identifiable in the literature. Based on these and the previous chapters and appendices looking at biosolids processing application and stability, WRC have constructed an starting list of locations/critical control points and related consideration which might be considered for inclusion in HACCP style analysis of odour risk exposure pathways.

2.3.6.1. Exposure pathway definition

Both stable and poorly treated biosolids can attract vermin. Sobsey et al. (2001) have reviewed the subsequent microbial transmission from animal and faecal wastes including exposure pathways for biosolids (Figure 22). Notably it shows related paths and vectors:

- the waste treatment system where the biosolids are produced;
- workers; and
- crops

The lesson to be taken here is that odour pathways definition should be seen as part of a larger HACCP analysis of all contaminants and sources associated with wastewater treatment. For example a sewage treatment plant will produce offensive odours which need to be distinguished for the purposes of the guidelines from those emanating from biosolids.

A generic HACCP path is proposed by the NBP (Figure 23). This indicates where unacceptable odour emissions might be expected to emanate.

Figure 24 shows a conceptual model reflecting biosolids odour fate and transport specifically. Henshaw et al. (2006, 2002) provide models of what complete on ground assessments could look like. Such models should ideally be validated for example using odour testers (Guo et al., 2005b, Newby and McGinley, 2004, Guo et al., 2005a).

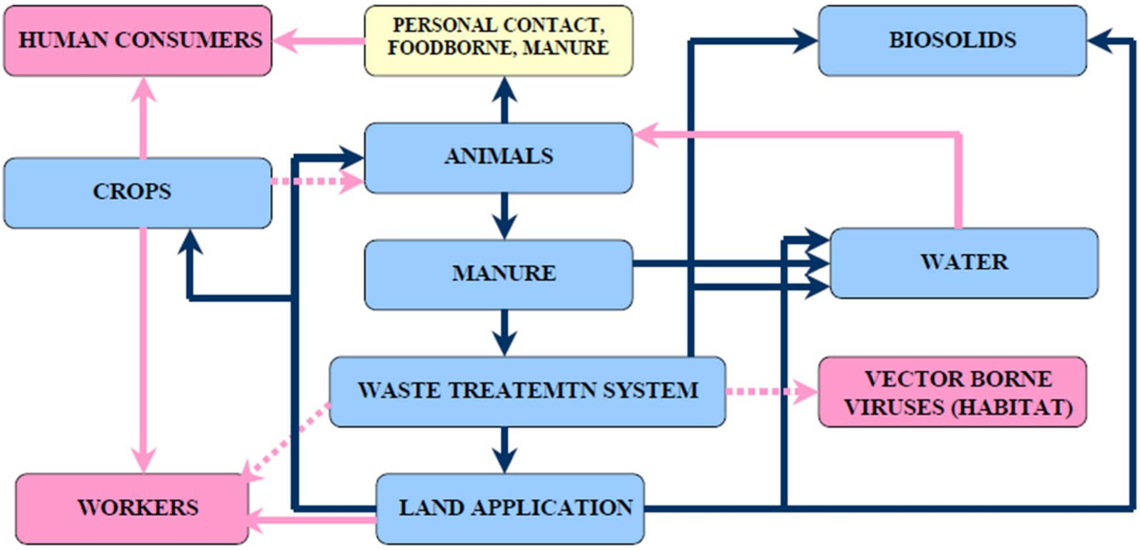


Figure 22. Sources and transmission pathways of pathogens to humans from animal agriculture (Reproduced from Sobsey et al., 2001)

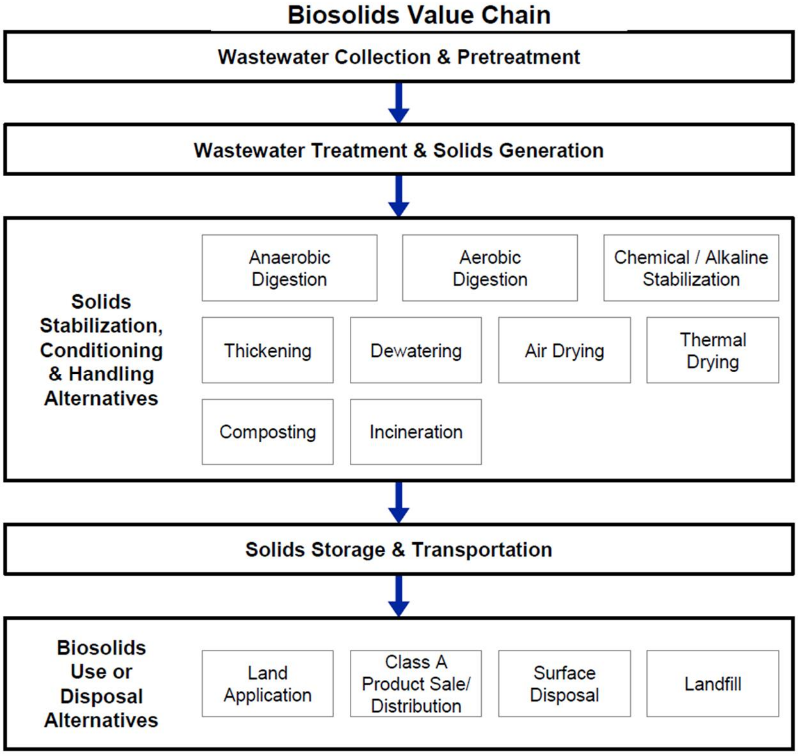


Figure 23. The biosolids "value chain" (National Biosolids Partnership, 2005 extracted from Appendix F)

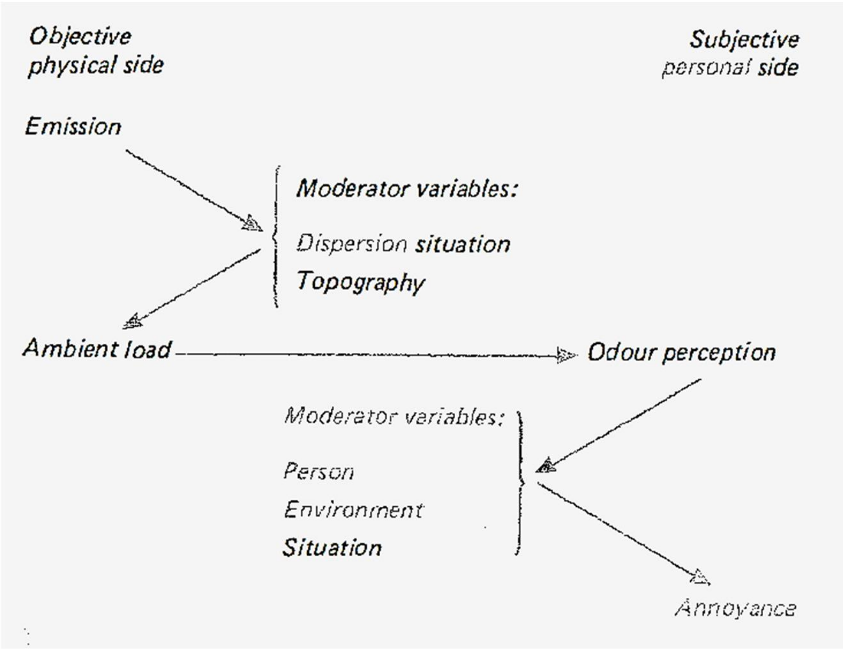


Figure 24. Odour specific conceptual exposure pathway map (Beuth Verlag GmbH, 1997)

2.3.6.2. Odour locations = emission points (Group Scoping)

Based on discussion within our WRC group we consider that identification of emission points is essential for scoping out monitoring needs recognising from the dose response literature above that this is not as simple as measuring conventional contaminants. Possible critical control points in a HACCP analysis are as follows:

XVIII. A possible list of points to include in guidelines where odour exposure needs to be assessed are:

a. Processing locations ï especially stabilization points - including
    i. Drying beds and Drying lagoons
    ii. Large windrows.
    iii. Composting arrangements (composted biosolids be included?)
    iv. Processing equipment and its maintenance e.g. washing
b. Transport including
    v. Trucks (full and empty)
    vi. Transfer points
    vii. Intermediate Storage points
c. Application fields and storage points and arrangement

Such checklists also need to consider the effects of biosolids generation scale.

2.3.6.3. Exposed populations (Group scoping)

Based on discussion within our WRC group we considered the following in respect to exposed population:

XIX. Allowance needs to be made for the different perception of odour by different exposed populations.

XX. In addition to considering the general community, sub populations for special consideration may include:

a. Children;
b. Immediately adjacent neighbours especially were monitoring might be located to ensure if they have complaints they can be verfied;
c. biosolids handlers (the current guidelines note the need to consider OH and S but provide not special guidance in respect to biosolids.
d. Other sensitive populations e.g. those with MCS syndrome, PTSD (a possible disposing trigger, high olfactory sniffers;
e. Stakeholders with different cultural and environmental expectations.

2.3.6.4. Exposure concentrations and intakes (Group scoping)

Based on discussion within our WRC group in regard to estimation of we considered that:

XXI. Routine detailed air fate and transport and exposure modelling appears feasible and desirable and should yield odour concentration PDFs which can be used at the least for decision support.

XXII. The guidelines should include verification and validation methodology and cover uncertainties such as measurement limitations (small point grab sample), the effect of Teflon bags e.g. adsorption, storage, and loss of odour during transport to analysis point. Professionally trained and calibrated panellists are needed for odour estimation;

XXIII. Modelling should allow for dilution to low OD units, different odourants and associated uncertainties including what individual chemicals might be present, the impact of chemical combinations and relative odourant contribution.

XXIV. Degradation should be considered/incorporated and cover rates and influences notably oxidation, solar exposure, temperature and humidity.

XXV. Odour assessments, being concentration focused rather than load focused, should not generally require estimates of intakes (as against probability of exposure) ï so only ambient concentration probability density functions are needed, though if intake is a concern references are already available here (EnHealth Council, 2012a).

2.3.7. Risk characterization

2.3.7.1. Odour, health risks and benchmarks

The literature here is relatively straightforward and has been reviewed above. Henshaw et al. (2002) provides a case study of how an assessment based on hazard assessment and exposure assessment would work. This includes illustrations of odour footprints and response estimation models. A further paper of this group provides models for the products of odour risk characterization (Henshaw et al., 2006).

In respect to biosolids worker exposure, Paustenbach and Gaffney (2006) reviewed the ñcurrent research regarding the relationship between odor perception or irritation and setting an occupational exposure limit (OEL).ò Important observations in this review were:

- ñIn the United States, OELs have attempted to avoid chronic irritation, rather than simply odor detection, in most workers.ò
- ñIn other countries, it is accepted that a significant fraction of the workforce may recognize the odor or irritant but, lacking adverse effects, it is considered acceptable. For all organizations, the goal of OELs is to keep workers healthy. However, in the case of odorous chemicals, more stringent guidelines may be necessary to keep risk perception and subsequent symptom reporting, low. This is problematic since risk perception is strongly based upon individual biases, and it is technologically infeasible to protect all workers from recognizing unpleasant odors. Therefore, the challenge surrounding this issue is to determine how to set the OELs of odorous chemicals best while balancing engineering feasibility. Furthermore, in some instances, regardless of the magnitude of the specific OEL, additional dialogue with employees with respect to the relationship between odor detection and risk perception may be needed for the OEL to be considered tolerable.ò
- ñFor practical reasons, the current objective of organizations charged with setting OELs for chemicals is to identify concentrations that do not cause irritation or widespread reports of unpleasant sensory stimulation in the vast majority of workers (e.g., about 80ï 95%).ò

In regard to establishing benchmarks against which exposure levels can be assessed as being acceptable or otherwise, Nicell (2009) provides a useful summary table reproduced in Figure 25 which indicates a degree on concurrence on acceptable ôOdour limitö especially given measurement uncertainties. More variable though is the averaging times and percentiles which range from 1s to 90d and 98th to 99.9th percentile respectively. **When establishing what is appropriate and how it odour to be measure the Guidelines should clarify why a particular compliance frequency has been chosen.**

Location	Odour limit (OU or equivalent)	Averaging time @ compliance frequency[a]
Bay Area Air Quality District (San Francisco, USA)	5 (fence line)	Applied after at least 10 complaints within a 90 day period
Colorado (USA)	7 (residential or commercial	Scentometer[b]
Connecticut (USA)	7	Scentometer[b]
Denmark	0.6–1.2 5–10	1 h @ 99% 1 min @ 99%
Hong Kong	5	5 s
Massachusetts (USA)	5	1 h
Netherlands	0.5 (sensitive receptors)	1 h @ 99.5%—for new facilities 1 h @ 98.0%—for existing facilities
Newbiggin-by-the-Sea and Derby WWTP (UK)	5	Not specified @ 98% compliance
New Jersey (USA)	5	5 min or less
New South Wales (AU)	2 (urban) 7 (rural) 15 (area source)	1 s @ 99.5% 1 s @ 99.5% 1 s @ 99.5%
New Zealand	2	1 h @ 99.5%
North Dakota (USA)	2	Scentometer[b]
Oregon (USA)	1–2	15 min
Philadelphia (USA)	20 (residential)	<100 h/yr non-compliance)—wastewater treatment plant
Queensland (Australia)	10	1 h @ 99.5%
San Diego WWTP (USA)	5	5 min @ 99.5%
Seattle WWTP (USA)	5	5 min
South Australia (AU)	2 (2000 persons) 4 (350–1999) 6 (60–349) 8 (12–59) 10 (residence)	3 min @ 99.9%
Taiwan	50 (petrochemical park)	Not specified
Tasmania	1	3 min @ 99.9%
Western Australia (AU)	2 4	3 min @ 99.5% 3 min @ 99.9%

[a] In cases where compliance frequency is not quoted, the stated limit on odour concentration is assumed to be a maximum.

[b] A scentometer is a device that measures odour concentration in the field. Since it is an "on-the-spot" measurement, it appears to be a near-instantaneous measure of odour, rather than a time-averaged value.

Figure 25. Illustrative odour guidelines (Reproduced from Nicell, 2009)

2.3.7.2. Benchmarking, odour regulations, guidelines and decision support (Group scoping)

Based on discussion within our WRC group we considered:

I. despite their limitations reference threshold emission rates and concentrations are still needed for different stabilisation processes and reuse options;

II. toxicity/disease causing odour levels should be identified relative to odour thresholds where possible;

III. that OD units rather and chemical analyses should be the preferred basis for assessing whether odours are acceptable or not despite the complications this introduces;

IV. the introduction of DALYs appears conceptually feasible but the required factor data are not yet available sufficient for benchmarking;

V. while the conceptual solution provided by odour dose response algorithms seems sound, further work on the diversity of subpopulation sensitivity to odours is also needed.

2.3.8. Risk management

In the opinion of Henshaw et al. (2002):

ñIn general, the owners of facilities producing odours would prefer not to gamble on a particular court's interpretation of whether a particular odour is deemed a nuisance. The facility owners would prefer to know a priori whether a particular odour will be acceptable, in the same way that emissions of conventional pollutants are deemed acceptable or unacceptableò

In short the first rule of odour risk management should be to site, scale and design biosolids processing, and disposal/recycling sites and transport arrangements sufficient to prevent nuisance in the first (e.g. late night transport, use of management systems proven to minimize odour emissions). Such avoidance is elementary risk management and little more needs to be commented except to note:

1. The previous and subsequent appendices of this review provide guidance on how to improve biosolids odour management.
2. Compliance/consistency with risk management standards and guidelines seem the best approach to providing facility owners with certainty.

2.3.9. Uncertainties and reality checks

2.3.9.1. Use of 'rational' risk assessment for decision support

While conventional ERA appears to offer a órationalô solution to sound biosolids management one difficulty with this approach with odours is may suffer from limitations characteristic of the órational methodô (Healey, 1983).

In environmental planning theory the rational method is defined as:

ñsystematic and explicit relation of ends to means and vice versa, the logical presentation of argument, and the systematic relation of evidence to argument.ò

While this seems unobjectionable the troubles emerge when planning for the siting of ódirty public thingsô when these become political (Allison, 1986). It is hard to think of anything that the public would conceive of as more ódirtyô than sewage sludge/biosolids. A discussion of the limits of the rational method can be found here (Allison, 1986, Kiernan, 1983, Healey, 1983).

Kemp et al. (2012) illustrate what had happened as a result of insufficient recognition of the limits of the rational method for the related and analogous ‘yuk’ issue of recycled water. They highlight how essential open and honest communications is essential to avoid public backlash and ‘scare campaigns’.

We do not suggest by this that formal rational odour risk assessment is not warranted or is not the best tool currently available to minimize odour problems. One great benefit of using a proven framework is it aids transparency at least to those familiar with odour fate and transport concepts.

Rather we are suggesting that guidelines should not promote presenting the outcomes of odour risk assessment as the last work but as information providing decision support, bearing in mind all stakeholder needs and concerns. This could also have the benefit of supporting those in communities who are in the main sympathetic to well designed biosolids recycling (Urbis, 2010).

2.3.9.2. Poor definition of impacts

The impact of odours on individuals is still imperfectly defined. On top of this is the impact on the social fabric of an area where any noxious odour is generated e.g.:

“Large-scale concentrated animal feeding operations cause other environmental health risks for those living in these areas. Areas that are dominated by concentrated animal feeding operations have odor pollution, which may result in decreases in neighbourliness, social cohesion, and trust, increases in social conflict, and alienation” (Shoff, 2012)

Further, odour is not the only poorly studied or defined risk in agricultural settings (Frank et al., 2004) and odour emissions exists in this larger context and responses may reflect the latter.

2.3.9.3. ‘Greenwashing’, the image of biosolids and its public reaction to odours

The current NSW guidelines open with the following statements (NSW EPA, 1997):

“The NSW Government's biosolids management policy is to encourage the beneficial use of biosolids where it is safe and practicable and where it provides the best environmental outcome.”

“Not only does raw sewage include a plentiful supply of water, but the solids component is rich in essential nutrients such as nitrogen, phosphorus and organic matter; and these are in a form that is highly suitable for assimilation by plants. As a result, there has been an increased interest in finding ways to reuse both the water and solids components of sewage in a manner that is cost effective, environmentally sustainable and safe from a public health perspective.ò

This positive view of biosolids reflects the USEPA (1995) position e.g.

ñThe reader will notice that throughout this document sewage sludge is referred to as biosolids. Biosolids are the primarily organic solid product yielded by municipal wastewater treatment processes that can be beneficially recycled (whether or not they are currently being recycled). The term biosolids is used in this document to emphasize the beneficial nature of this valuable, recyclable resource (i.e. , the use of the nutrients and organic matter in biosolids as a fertilizer or soil conditioner).ò

Unfortunately these positive messages omit the fact that significant opposition to biosolids has also developed especially in the USA. These concerns at least at the perception level, do not appear to have been satisfactorily addressed and arguably they have been óGreenwashedô

A text which captures the concerns is the book authored by Stauber and Rampton, óToxic Sludge is Good for Youò. The popular, well cited (n=610 in GoogleScholar), highly rate book http://www.goodreads.com/book/show/659246.Toxic_Sludge_Is_Good_for_You (TSIGFY) is easy to identify and itemizes a range of concerns.

Of particular concern is Chapter 8 óThe Sludge Hits the Fan (Stauber and Rampton, 1995). The authorõs central concern was not solely biosolids quality or immediate risks to soil and water quality but also that the development of Biosolids management has historically involved ñGreen-washòng and problematic policy development on the part of the biosolids industry represented by the Water Environment Federation (WEF) and the USEPA itself.

óGreenwashingô is described by Segev et al. (2016)õs article in the Journal of Advertising as follows:

ñAdvertising plays a major role in generating public awareness about environmental issues, communicating a green brand image, and driving consumer demand for green products (Grillo, Tokarczyk, and Hansen 2008). Nevertheless, green advertising faces challenges as consumers are becoming increasingly skeptical about its credibility and usefulness (PR Newswire 2010). While many companies use advertising to communicate their genuine attempts to minimize the environmental impact of their brands and products, others exaggerate or even fabricate the environmental impact of their offerings (Carlson, Grove, and Kangun 1993). Referred to as greenwashing, such environmental claims include vague, unsubstantiated, and potentially misleading statements communicated in green advertising or marketing material (Fernando, Suganthi and Sivakumaran 2014). Greenwashing potentially erodes the consumer market for green products and services (Furlow 2010), distances potential investors interested in environmentally friendly firms (Delmas and

Burbano 2011), and negatively impacts the credibility of the organization and its perceived performance (Newell, Goldsmith, and Banzhaf 1998). Therefore, the question of whether green advertising communicates a sincere environmental message is of primary importance.ò

The concept and the problem it generates is widely discussed in the literature having arisen in response to the study of Carlson et al. ós (1993) observation (cited directly 436 times ï GoogleScholar 2016) that:

ñResults suggest that those claims which extol the environmental benefits of products and those that are designed to enhance the environmental image of an organization are most prone to be considered misleading and/or deceptive.ò

As an indicator of how controversial biosolids application can potentially be, though TSIGFY reviews many controversial highly issues including chlorinated herbicides and pesticides, nuclear weapons development and tobacco, the title itself was, in fact, inspired by biosolids. Reflecting this distrust in industry and the government there has been backlash from environmental groups interested in land management especially those interested in óorganic foodô production (e.g. Smith, 2012, Vestel, 2010 , Stauber, 2016 (accessed), Ferguson, 2009). It is even suggested that biosolids application is among the most controversial of food/agriculture industry practices, along with food irradiation and the use of genetically engineered seeds and microorganisms (Lupp, 2008, Houston, 2012, Constance et al., 2008), óthe big threeô as one author put it.

As a result, rather than being seen as beneficial method for recycling nutrients from human use back to the environment in the manner of say composting, biosolids is largely banned from óorganic farmingô[13] . An illustration of this sensibility can be found here (Organic Consumers Association, 2014). This position appears to be reflected in organic food policy in NSW as evidenced by biosolids being perceived *in toto* as unsuitable for organic farming as evidenced by current industry positions (Australian Organic Ltd, 2013, NSW DPI, 2011).

Were this a case of fringe politics driven misunderstanding, it might not be a concern for Guideline development. Unfortunately White et al. (2011) in the Journal of Business and Economics Research indicate the development of the name óbiosolidsô, is indeed an archetypal example of perception management by the public relations industry:

ñAs every public relations expert knows, for an idea to be accepted by an audience it must be perceived as congenial to the recipientôs accepted values. For example, rather than call their product ñsewage sludge,ò the water treatment industry now calls it by the less tainted

[13] It is interesting to note that the term óorganicô has a long history which precedes the development of óorganic chemistryó https://en.oxforddictionaries.com/definition/organic

term, ñbiosolids.ò Regardless of what it is called, it is a useful product. But by minimizing its origins, it is more acceptable to the public (Biosolids.com, 2007).ò

The US industry player, Biosolids.com (2016 (accessed)) also appears to confirm the term was developed with public relations in mind:

ñOrigin of ñbiosolidsò name...While the practice it describes is not entirely new, the word "biosolids" is. Its use started a little more than a decade ago. The Water Environment Federation (WEF) solicited suggestions for a name after water quality professionals searched for a new expression to more accurately describe the treated sewage sludge that could be used for agriculture and as a soil amendment. "Biosolids," an abbreviated variation on the biological processing of wastewater solids, was one of 300 responses to WEF's call for suggestions. WEF formally recognized the term in 1991 and most state and federal agencies use it today.ò

The reason we have raised this concern here is not to take sides either way but rather:

- To alert NSW EPA to the potential intensity of opposition to biosolids land application and hence the need for/centrality of transparent and open public consultation when developing the new guidelines;
- The need to prove to stakeholders that sewage sludge contains much lower/tolerable levels of contaminant compared to the past when control was poor and biosolids could rightly have been viewed as toxic sludge[14];
- To alert EPA to literature from both sides of the argument which have divergent positions of whether biosolids application constitutes beneficial reuse or not.
- Because the public attitude to biosolids odour is as much about sensory perceptions as specific risks of concern and so concerns may be raised in discussion of odour.
- Being aware of this history may help reduce the conflict that marked the introduction of recycled water.

2.3.9.4. Perception concerns generally

The issue of Greenwashing relates to the more general issues of biosolids perceptions and concerns particularly as they relate to odour and how or whether the guidelines should deal them. The issue is raised here as odours can trigger a range of other responses ranging from very positive to very negative as with wastes such as biosolids (Davis et al., 2013, Davis, 2010).

[14] For example as part of the 1990s era SOLP program SW collected data of 107 Schedule 10 chemicals. WRC reviewed the risk from the water concentration and found most were below hazardous levels - see ROSER, D., KHAN, S., DAVIES, C., SIGNOR, R., PETTERSON, S. & ASHBOLT, N. 2006. Screening Health Risk Assessment for the Use of Microfiltration-Reverse Osmosis Treated Tertiary Effluent for Replacement of Environmental Flows. Centre for Water and Waste Technology, University of New South Wales.

Tourism is an increasingly important industry in regional Australia. The desirability of a locality as a tourist destination appears to be tied in with odour, vision and haptic (touch) senses and each of these in turn interacts (Ghosh and Sarkar, 2016) and with what is merely written about a place (Fenko et al., 2014). It follows that when siting biosolids management zones the latter should be taken into account as with other nuisances such as noise.

An increasing concern for the public in respect to recycled water reuse is the impact of endocrine disrupting compounds (EDCs). Their fate after biosolids processing remains incompletely determined (Citulski and Farahbakhsh, 2010). So this may emerge as a perception consideration in the future.

2.3.10. Analytical and assessment methods

Hayes et al.(2014a) describes a range of such methods. The main laboratory based methods are primarily:

- Analytical methods (notably for example: GC-MS for specific chemicals)
- Gas chromatographyï mass spectrometry combined with olfactometry
- Air dispersion modelling and input data collection to understand off site transport and impacts and their varying likelihood
- Sensory arrays for some key chemicals

This work needs to be complemented by community assessment methodologies designed to identify community concerns and needs in a fully transparent fashion. Methods include:

- Structured surveys
- Qualitative research
- Social engagement

An interesting example of the outcomes of social engagement is McDevitt et al.ǒs(2013) work which shows that the exercise can generate more diverse responses than might be expected from apply basic engineering>disposal management. This may affect the preferred methods of stabilisation and recycling in any particular instance.

2.3.11. Conclusions – Adaptation of odour hazard, health, and toxicity risk assessment and management concepts to biosolids odour management

1. ERA style assessment and management of odour seems appropriate and largely defensible. It provides a scheme for holistically analysing biosolids production transport storage and fate comprehensively. Best practice in regarding to biosolids and odour management in related fields e.g. animal manure management is heading in essentially the same direction.

2. This conclusion is despite enHealth's misgivings that odour is does not pose a risk in the familiar sense. This might be addressed by reference to the concept of 'risk' being more than human health risk.
3. One limitation is that the ERA / HACCP style analysis does not immediately indicate how to respond to biosolids management hazard events and process malfunctioning. However this analysis should identify critical control points where failures may occur and other management tools e.g. Fault Tree Analysis could provide predictions and facilitate scoping of responses to hazardous events.
4. In regard to adaptation of the odour concept to an ERA framework the following seem to be most challenging:
    a. NSW EPA need to consult with NSW Health to reach agreement of whether odours constitute a risk and what is the appropriate response to concerned populations and individuals who are unusually sensitive to odours.
    b. Odours responses vary greatly between populations and type of response of concern. These variations need to be dealt with systematically.
    c. There may be different odours depending on the stabilisation process. Covering their management efficiently needs to be part of the guidelines.
    d. Responses to, and risks from, odours is tied in closely to human psychology. This is important for the following reasons:
        i. Psychosomatic effects have potential to be debilitating. This needs to be addressed while avoiding if possible biosolids managers not having to address problems which are not their responsibility.
        ii. Odours provide a form of warning indicator in built into people analogous to those involving scientific analysis e.g. bacterial indicators. Like the latter they are very useful even though they are not perfect indicators of clear illness/injury risks.
        iii. Odours and odour response likely inter-relate to responses to touch and sight. Recognition of this is needed when siting facilities.
5. High quality community consultation is possibly all the more important for biosolids than when managing other Environmental Values. In part this reflects the relationship between odour and human perception. In part this is because there appears to be a problematic history of the biosolids management industry trying to manipulate public responses in a cynical manner. Even though this perception comes mainly from the US it appears that there is potentially strong opposition to biosolids 'beneficial reuse' which may need to be addressed transparently to demonstrate the latter indeed is defensible.

2.4. Stability management

2.4.1. The vexed concept of biosolids 'Stability'

WRC's group discussion about stability quickly revealed this was a more difficult issue than odours to put into a risk management framework. Some perceived condundra were as follows:

- There is as yet no general definition of biosolids 'stability';
- Developing a general definition may not be practical because of the diverse materials that constitute 'stabilised' biosolids. This confounds the standardization of the concept and in turn identification of monitoring methods;
- 'Stability' is not of itself conceptually a risk but is more its opposite;
- Material that has been stabilised e.g. by drying, can be destabilised in respect to odour production by changing pH.

This situation compares with composting where a different term 'maturity' is used to indicate when a relatively stable soil like product has been produced (Wichuk and McCartney, 2010) and its behaviour will not change substantially upon incorporation into soil. This latter paper reviews and identifies the assessment bases for maturity assessment. It shows for a given material many monitoring methods are available such as CO_2 evolution, seed germination rate, water-soluble organic carbon (WSOC), UV and DOC analysis to assess the presence of soluble carbon (Domeizel et al., 2004, Zmora-Nahum et al., 2005) which can used to assure a stable product has been obtained irrespective of the method.

The question of what biosolids stabilisation means seems well recognized in biosolids management industry (Switzenbaum et al., 1997, Tsang and Jr., 2005, Bernal et al., 2009, Ko et al., 2008). And no definition is provided by Baldwin et al.s (2001) extensive review on biosolids and sludge management generally.

2.4.2. HACCP and stability

The NBP (National Biosolids Partnership, 2005) do not actually define stabilization. But they do identify a range of general Critical Control Points and Operational Controls (as well as specific ones which are process related):

- "Solids Loading Rate
- Operating Volume
- Detention Time
- Temperature
- Mixing
- pH
- Volatile Acids/Alkalinity

- Nutrients
- Gas Production
- Scum and Foam Production
- Failure Indicatorsò

This highlights the use/potential of a HACCP and risk assessment framework for managing stabilisation issues.

2.4.3. Partial solutions

One partial solution may be where biosolids are composted, to simply use the concept of maturity, as assessed by standard methods and maturity criteria identified in numerous tables by Wichuk McCartney(2010) and required for the production of mature compost.

A second partial solution for non-composted biosolids may be the definition of Fytili and Zabaniotou (2008);

ñSustainable sludge handling may be defined as a method that meets requirements of efficient recycling of resources without supply of harmful substances to humans or the environmentò

This latter has the benefit that it means that the definition can be flexible. Its downsides are that it is vague and stability requirements need to be better specified. This could be done using a systematic review (Centre for Reviews and Dissemination, 2009, Moher et al., 2009) of the literature (Zubillaga and Lavado, 2003, Sánchez-Monedero et al., 2004, Fytili and Zabaniotou, 2008) to obtain a consensus of what does and does not constitute a stable product.

2.4.4. Is 'Stability'/Maturity an Environmental Value

Neither ôstabilityö nor ômaturityö constitute quantitative end points of the kind used in a risk assessment and management frameworks. This is because these states are not actually a deviation from the desired state. A mature compost or stable biosolid is in fact the converse, the desired state that is considered achievable whereas ñ*risk (is simply the*[15]*) effect of uncertainty on objectives"* (ISO, 2009).

The concepts of stability, or alternatively maturity, are probably closer to an ôEnvironmental Valueö (section 2.2.6) whose achievement in terms of parametric measurements has yet to be precisely specified and needs to be determined on a case by case basis depending on the original sludge type, the stabilisation process and the end use.

In the framework for regulatory (guideline) design Tsang and Smith (2005) identify

1. Five acceptable stabilisation processes:

[15] Implied by added by WRC

- Aerobic digestion
- Anaerobic digestion
- Air drying
- Composting
- Lime stabilization

2. Five further pathogen reduction processes which would be acceptable in Australia[16]:
    - Composting
    - Heat drying
    - Heat treatment
    - Thermophilic aerobic digestion
    - Pasteurization

They do not unfortunately make clear what properties each realistic stabilization + pathogen reduction combinations would produce though they do indicate odour would be a major criterion of stabilised or mature biosolids. **So a first step for NSW EPA would be to define what they constitute in terms of microbial chemical or odour production. The current guidelines specify processes for different grades but not what stabilised biosolids look like in respect to risk and parameters reflecting a stable product.**

WRC concludes that what stabilise biosolids constitutes especially in respect needs to be developed for each combination used or proposed for use in NSW. This would constitute the references cases against which risk odour, pathogen and chemical risk likelihood and consequence could be assessed.

2.4.5. A risk management perspective on stability

Clarification of what constitutes stable biosolids should in turn allow ready identification of biosolids properties which constitute hazardous events requiring remedial action. Events where processing does not stabilise biosolids according to such specifications, or events which destabilised final process biosolids need to be defined along with their chemical, biological and odour impacts. A model for this is the working guide of Nadebaum et al. (2004). An analogous document or section in the final guidelines would go a long way to ensuring standardization of operational biosolids stabilization.

Alternatively the concept of stable biosolids might be essentially dropped. Food and the application of HACCP provides a possible analogy here as follows:

- Each typical basic food is not single ‘stable’ products but a semi-stable material which is sequentially processed, transformed, transported and preserved in states of

[16] Beta and gamma ray irradiation are also identified as possible methods.

low biological activity prior to its final fate (consumption, composting or waste to garbage).

- The biosolids management train is comparable with the exception it is ćconsumedôby soil rather than people.
- Food like biosolids vary in their degree of stability which depends on how far they have been processed to ensure a long shelf life.
- HACCP has been developed to identify where the processing, transformation etc. can go wrong and needs careful management.

There is a need to complementing a clarification of what constitutes stabilization, with advice on what biosolids managers should do when normal management fails.

Such events involving deviation from ideal biosolids characteristics could be quantified in terms of event, fault or failure scenarios (i.e. Tools 13, 14, 15, 16 in IEC/ISO, 2009). So these risk management tools seem to have a place in developing the management of insufficiently stabilized, or destabilized, biosolids. The significance of the risk arising could also be dealt with in the usual way by comparing the impact against baseline/tolerable microbial chemical, or as discussed above, offensive odour risks.

2.5. Vermin and vector attraction

2.5.1.1. Key concerns

The key concerns in respect to vermin appear to be flies and rats.

Cattle manure has significant loads of pesticides which are present with aim of controlling insect pests and parasites (Coleman et al., 2013). This however is not the case with biosolids and so vermin control is more problematic.

Biosolids and other faecal residues provide an excellent habitat for house flies and stable flies including in Australia (Dadour and Voss, 2009, Doud et al., 2012, Doud, 2011).

Both house flies and Stable flies have long been a concern for their disease transmission potential (Bureau of Entomology and Plant Quarantine, 1952, Chakrabarti et al., 2010).

Pathogen transmission is the main concern and this can include protozoa and bacterial pathogens including mycobacteria, Bartonella, enterohaemorrhagic *E. coli, Campylobacter, Helicobacter, Aeromonas, Yersinia and Salmonella* (Szostakowska et al., 2004, Fischer et al., 2004, Talley et al., 2009, Chung et al., 2004, Graczyk et al., 1999, Mian et al., 2002, Shane et al., 1985, Rosef and Kapperud, 1983, Grubel et al., 1997, Nayduch et al., 2002). Transmission can be mechanical or involve intragut reproduction. The topic has been reviewed by Graczyk (2000).

Sobsey et al. (2001) have reviewed the microbial transmission/exposure pathways associated with faecal wastes generally including biosolids. They consider in the case of rats the prime concern is also bacterial pathogens and illustrate the potential with a range of instances. A possible exception is Hepatitis E virus.

2.5.1.2. Monitoring

Methods for monitoring chemical and pathogens are dealt with elsewhere. Methods for assessing the magnitude of fly infestation of biosolids are available (Dadour and Voss, 2009, Doud et al., 2012, Doud, 2011). Also some ecology and tracking and tracing have been attempted (Chakrabarti et al., 2010, Urban and Broce, 1998, Taylor et al., 2007). However, complete methods for quantitatively assessing the scale and the risks arising from the transfer of pathogens beyond the biosolids location or even to biosolids worker have not been developed that we could tell.

2.5.1.3. Application of risk management

Conceptually the risk of vermin transport of pathogens looks to manageable via an ERA + HACCP based approach. However as far as we could tell no Quantitative Microbial Risk Assessment (QMRA) of fly or rodent borne transfer has been undertaken.

2.5.1.4. Conclusion

In summary vermin control is a concern related to biosolids stability and the underlying principles are understood. Also ERA + HACCP seems directly applicable. However:

- The scale of risk posed by flies and rodents does not appear to have been quantified.
- This issue is arguably one where harmonization within the guidelines is needed i.e. between the odour/stability/vermin sections and the microbial risk assessment and management sections.

2.6. Modelling

2.6.1. General

Conceptual and quantitative modelling play an increasingly important part in human and environmental health and risk assessment and management. It is clear this applies also to odour (risk) assessment and probably to vermin as well. If a HACCP + ERA approach were adopted it is suggested the issue of stability would be implicitly addressed.

Modelling for odour (risk) assessment, is well developed as evidenced by the quantification of odour dose response and air transport modelling. The reasons for modelling odour production and dispersion are various but the main ones are that:

- traditional monitoring cannot logistically be used to quantify all odour impacts and scenarios and models provide a way to understand what is conceivable, in particular rare high impact events;
- models can make allowance for biosolids operation scale allowing guidelines to be tailored to both large and small operations which pose less risk;

- models provide reality checks on observed impacts ;
- models assist in the process of making reasoning auditable beyond that possible with expert opinion alone;
- model scoping and construction can help identify or highlight knowledge gaps;.

The need for modelling has long been recognized e.g. the USEPA (1995):

ñGuide emphasizes the importance of **collecting relevant data and using appropriate models and assumptions (field-verified whenever possible)** in the establishment of pollutant limits and management practices that protect public health and the environment from reasonably anticipated adverse effects of pollutants in biosolids.ò

In the case of stability the concern is about how to minimise the occurrence of insufficiency stable or potentially unstable biosolids, which could lead, to excess malodour emissions and vector/vermin transmission of pathogens. Such events, failures and faults seem amenable to scenario based risk analysis, not especially targeted at final odour/transmission impacts but instead at minimising biosolids management objective failure.

In the case of vermin WRC did not identify any models. However, developing these would be useful first step in systematic identification of biosolid production and recycling practice weaknesses. Further this could provide conceptual frameworks of transmission that could be quantified and integrated into QMRA in future.

2.6.2. Transport and dispersion modelling

Air contaminant transport modelling is well established.

In addition to the references/examples identified above further modelling case studies illustrating how air modelling works can be found in these relatively recent works (Ormerod, 2001, Luhar et al., 2004a, Luhar et al., 2004b, Hurley et al., 2005, Hurley and Luhar, 2005, Hurley, 2006, Xing et al., 2007, Katestone Environmental Pty Ltd, 2009, Noonan, 2009).

The main local candidates for standard models appear to be AUSPLUME, CALPUFF and TAPM.

Two complications with odour transport and dispersion modelling (no including uncertainties associated with dose response modelling are that:

- Odorants may decompose during transit depending on solar radiation temperature and humidity.
- Odorants may form from precursor transformation.

The guidelines should probably assist their use by recommending when these might be used, their limitations and what any alternatives might need to achieve.

2.6.3. Process treatment modelling and dynamic and computerized fluid dynamics (CFD) modelling of storage and composting

Solid waste treatment processes have been subject to increasingly sophisticated modelling aimed at controlling and optimising these processes of interest.

With improved computing power and this has advanced from sophisticated empirical modelling (Lyberg and Hogland, 2004, Turner et al., 2005) to 2-D and 3-D mechanistic models (Finger et al., 1976, Mason, 2006) and most recently CFD models (Wu and Crapper, 2009b, Wu and Crapper, 2009a, Stehlík, 2009, Han et al., 2009, Landry et al., 2006).

These advances seem to promise methods from greatly improving understanding of biosolids changes and óstabilisationô behaviour. Such modelling is now taking place e.g. (Özdemir et al., 2014).

2.6.4. Dose response modelling

Dose response modelling appears sufficiently well developed for guidelines to recommend their use in odour and toxicity exposure work. **The guidelines could document examples of such modelling and propose preferred input coefficients and assumptions and dose response algorithms for biosolids emissions depending on how they have been stabilised and recycled or otherwise disposed of.**

2.6.5. Validation modelling of new and existing stabilisation processes

Following the development of national recycled water management guidelines based on the application of risk assessment and management (Environment Protection and Heritage Council, 2006) a further need identified was for guidance in validating treatment processes (Power, 2010). The problem at heart was that the available data on the effectiveness of treatment processes was of highly variable quality and the guideline values which were central were recognised to be insufficiently underpinned by the scientific literature on water treatment. Further to this, there were a range of difficult challenges such as efficient communication between project proponents and regulators and dealing with novel contaminants. This led to the National Validation series of projects (Australian Water Recycling Centre of Excellence, 2014 (accessed), Muston and Halliwell, 2011). The main function of these was to develop via research authoritative estimates of the effectiveness of various treatment processes particularly their disinfection capacity.

The experience of the water recycling community suggests the guidelines need to include recommendations on biosolids processing validation which could in the first instance be based on a meta-analysis of the literature.

2.6.6. General risk management, HACCP/ERA modelling and Bayes Nets(BNs)

HACCP/ERA modelling can integrate emission rates and quantities, dilution, transformation, fate and transport and receptor responses to assess odour benchmark exceedence likelihood.

This could be done using a series of interlinked models which were either empirical or mechanistic or a combination of both. Alternatively probabilistic relationships between nodes/critical control points could be quantified and used to construct inference models based on Monte Carlo or Bayes net software.

The latter option is noted reflecting WRCôs experience with recycled water (Roser et al., 2015). This indicated among other things the following:

1. BNs can facilitate far more than ERA. Virtually every ISO 31010 tool could be emulated using a Bayes net platform. In fact BNs appear to off a near universal systems analysis and simulation tool /language analogous to spreadsheets.
2. The two familiar risk modelling tools risk matrix assessment and HACCP can be emulated. BNs allow the construction of HACCP diagrams óon steroidsô i.e. the tree diagrams can be not only conceptual but also have programmatic integrity in the same fashion as relational databases.
3. BNs also offer near unlimited scenario evaluation within the limits of the inputs data and relationship assumptions. The allow backcasting from end desired results and so allow the conditions leading to them to be defined.
4. Once a BN has been constructed it is possible to ólearnô the probabilistic relationships between variables (nodes) through several optimization methods. Alternatively it is possible to learn what associated variables control a critical variable such as process failure likelihood in a manner analogous to regression analysis. The difference is that such ósemi-naïveô BNs can be then immediately used to identify critical combinations of determinants and how they impact the critical variable, and have the modelôs validity easily checked as well.
5. Input assumptions and probabilities are readily accessible and auditable unlike so many multifactorial effectively black box models.
6. BNs can include ólatentô or óhiddenô variables comparable to those used in artificial intelligence engines based on neural nets.

An illustration of BN use in biosolids management planning in Spain is provided by Passuello et a. (2012). They use BNs in combination with GIS analysis to identify preferred areas for biosolids land application. In line with best BN practice its construction involved extensive stakeholder inputs.

An important illustrative application to consider is BN application to Fault Tree Analysis. Lindhe et al. (2012) provide an excellent illustration of how FTA is done and can be used to identify critical failure points and situations ï in their case causes and repair of a malfunctioning water supply. The first model they discuss employs óANDôand óORôgates in an FTA which can be reproduced using BNs. The application of this to managing biosolids processing is self-evident.

Bayes net systems development also involves two critical ancillary activities which provide models for risk modelling practice generally:

- Systematic development often in consensus /group situations of models and agreement on inputs and structure (Kragt, 2009, Pollino et al., 2012, Chen and Pollino, 2012, Pollino and Henderson, 2010, Fenton and Neil, 2012);
- Post development model validation methods (Pollino et al., 2007, Marcot, 2012, Marcot et al., 2006).

Lessons for the guidelines in respect to modelling are as follows:

- BNs offer a single software platform for much conceptual and basic quantitative modelling of odour risks and impacts.
- BNs can address the desirability of employing all applicable ISO 31010 tools. This includes ERA, HACCP and Risk Matrix type modelling.
- BNs offer a means for collating process management data and defining variable interrelationships.
- Modelling guidance must include promotion of good construction practice and subsequent validation.

2.6.7. Decision making and utility

Increasingly there is a demand for environmental management works to minimise costs while achieving efficient sufficient resource management outcomes. One method of balancing costs it to calculate the benefits and dis-benefits of different management strategies (ISO 31010 risk assessment tool 30) e.g. in choosing between different biosolids stabilisation options.

Modelling can promote this by taking care of the complex calculations involved in applying formal probabilistic Utility. By calculating the óUtilityôof different options (Neter et al., 1988) it is possible conceptually to integrate stakeholder preferences into decision making.

Such formal utility assignment and identifying optimal decisions involves application of Bayesian statistics. In plain English this means to mathematically combine several ñpriorò probabilities for variables of interest e.g. rates of process failure, and calculate for different scenarios improved óposteriorôprobabilities for these and other variables of interest e.g. cost, risks. Ellison (1996) provides a useful outline of the concept of how (risk) managers can use Bayesian methods to infer better and worse ways to address environmental problems.

In the past Bayesian calculations were challenging to understand and employ. However this has largely changed with the emergence of Bayes Nets (see above) which among other things facilitate the calculation of ôUtilityô which as Korb and Nicholson (2011) explain provides a basis for ódecision makingô

ñagents assign utility (or, value such as a monetary or risk one) to the situations in which they find themselves. We know what we like, we know what we dislike, and we also know when we are experiencing neither of these. Given a general ability to order situations, and bets with definite probabilities of yielding particular situations, Frank Ramsey (1931) demonstrated that we can identify particular utilities with each possible situation, yielding a utility function.ò

Such calculations are now straightforward. Bayes Nets programs including Norsysõs Netica (Norsys Software Corporation, 2013) include specialized nodes (variables) designed to calculate Utility given different decision options/scenarios. Korb and Nicholson(2011) describe and illustrate the process with some plain English examples. Other software which can perform the same task include Palisade @ Risk (Palisade Corporation, 2013, Palisade, 2010). This add on to Excel facilitates Monte Carlo modelling and is popular for many risk modelling purposes including QMRA. Itõs professional version includes an add-on called Precision Tree which can also calculate Utility based on Bayesian principles.

An important function of guidelines is to ensure the concepts and methods it promotes are intelligible to a wide audience e.g. through explaining concepts in plain English. In this regard ôUtilityô presents a challenge as it means different things to different people and economists have taken on a particular definition relating to monetary value even though this is not the only option. A further problem is that ódefinitionsô of Utility are often obtuse or highly mathematical and require extensive theoretic knowledge to grasp (Good, 1952, Friedman, 1955, Bernado, 1979, Berger, 2013). Fortunately Broome (1999) provides a plain English explanation of the concept and these complications:

ñôUtilityõ, in plain English, means usefulness. In Australia, a ute is a useful vehicle.[17] Jeremy Bentham[18] specialized the meaning to a particular sort of usefulness. ôBy utilityõ, he said, ôis meant that property in any object, whereby it tends to produce benefit, advantage, pleasure, good, or happiness, (all this in the present case comes to the same thing) or (what comes again to the same thing) to prevent the happening of mischief, pain, evil, or unhappiness to

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[17] Yes this Oxbridge Don did say this in this introduction to óutilityô.

[18] Notorious for having been taxidermed and displayed at Imperial College except when attending College Council meetings https://en.wikipedia.org/wiki/Jeremy_Bentham#Death_and_the_auto-icon

the party whose interest is considered.ö1 The óPrinciple of Utilityô is the principle that actions are to be judged by their usefulness in this sense: their tendency to produce benefit, advantage, pleasure, good, or happiness. When John Stuart Mill speaks of the óperfectly just conception of Utility or Happiness, considered as the directive rule of human conductô, he is using óUtilityô as a short name for this principle.2 óThe Greatest Happiness Principleô was another name for it. People who subscribed to this principle came to be known as utilitarians.

Benthamism entered economics in 1873, with the publication of W. S. Jevonsõs Theory of Political Economy. Jevons quoted Benthamõs definition of óutilityô and announced: óThis perfectly expresses the meaning of the term in Economy.ô But after Jevonsõs time, the meaning of óutilityô in economics shifted. The word came to refer not to the tendency of an object to produce good, but to the good an object produces. By a personõs óutilityô, economists came to mean not the personõs usefulness in promoting good around her, but her own good. óUtilityô came to mean good. This meaning has since been overlaid by yet another, which I shall be describing later. But it still persists as one of the current meanings of óutilityô

é é Axiomatic utility theory

The confusion stems from a new meaning that was assigned to the word as axiomatic utility theory developed during the course of the twentieth century. The axiomatic theory sets out from a personõs preferences. It proves that, provided these preferences conform to some axioms, they can be represented by a óutility functionô The values taken by the function are called óutilitiesô The sense in which the function represents the preferences is this: of any pair of alternatives, the function assigns a greater utility to the one that is preferred. So óutilityô acquired the meaning: the value of a function that represents a personõs preferences. This is by now the official definition of utility in economics. For brevity, let us say: utility is that which represents a personõs preferences.ò

In respect to these quotes the following from the above quote is notable:

ñThe values taken by the function are called óutilitiesô

This suggests notionally that Utility Theory offers a way of grounding and comparing the relative importance of competing ñEnvironmental Valuesò (see Section 2.2.6) as well as costs and benefits. This may be important as it is clear than unlike health risks such as pathogens and toxic chemicals odour risk invokes distinctive and different values in different people. In apply óUtilityô theory extreme utilitarianism - maximum utility ñgreatest good for the greatest numberò (safe disposal of large city biosolids v. odour impacts on small rural communities where soil incorporation takes place) - would seem too much of a stretch as city would always win out over country. And there are in fact many other ways to develop decision criteria (e.g. Dowie and Kaltoft, 2011, Dowie et al., 2013, Dowie, 2006) including

Multi-criteria decision analysis (ISO 31010 2009 Tool 31). However it could still provide relative Utility estimates which could be used for decision support ï as against fully determining decide optima.

A possible use for óUtilityô modelling which might be covered in the guidelines is its use to choose between different competing biosolids management options and assessing when benefits are greater that its disbenefits.

3. Appendix 3 - Risk management within an Environmental Management Systems framework?

The previous Appendix looked at using a formal risk management framework and tools to manage biosolids odour, stability and vermin and harmonize this with pathogen and toxic chemical management. While applying the risk management concept appears feasible the discussion did not explore how odour, stability and vermin management would fit inside the wider institutional environment within which biosolids management operates. This contrasts with previous guidelines (NSW EPA, 1997) which also for example:

- List possible land types where application appears appropriate;
- Provides storage advice
- Identifies applicable NSW legislation;
- Provides ways of calculating land application rates;
- Recommends minimum monitoring regimes and analytes;
- Identifies the need for records maintenance.

All of this is important information which should be retained in the new guidelines. On the other hand these older guidelines are relatively prescriptive which makes introduction of new technologies and better procedures difficult. So a new guideline format seems warranted.

Technical information such as that above should be retained in the new guidelines possibly in a new format. **This could be done through the addition of resource appendices** such as:

- **Factsheets** along the lines of those seen in the Australian Drinking Water Guidelines (NH&MRC, 2013);
- **Summary technical tables and worked examples/case studies** such as seen in the Recycled water guidelines (Environment Protection and Heritage Council, 2006).

Beyond this is the question of how to present the larger descriptive institutional context, i.e. the conceptual framework within risk management and technical information would sit. Modern examples of this can be found in the Australian drinking and recycled water guidelines (NH&MRC, 2013, Environment Protection and Heritage Council, 2006). These are suggested because the industry is the same and they are concerned with developing a related, safe minimally polluting product and providing both conceptual and technical support.

3.1. A management system based strategic framework for risk management implementation

Further to this, and by way of a checklist of what elements should be included in the new overall guidelines, EPA might also consider using an Environmental Management Systems framework.

Since the 1997 biosolids guidelines were developed, there have also been developments on the institutional side of environmental management focused on ensuring/generating a satisfactory end-product. In particular there has been the introduction of the Environmental Management System methodology starting around 1996. This management methodology has also been taken up by water authorities complementing risk management:

ĩIn the Australian water industry, risk management and quality management are increasingly being used as a means of assuring drinking water quality by strengthening the focus on more preventive approaches. Some water authorities have implemented management systems based on ISO 9001 (Quality Management), ISO 14001 (Environmental Management), AS/NZS 4360 (Risk Management) or more recently the Hazard Analysis and Critical Control Point (HACCP) system that has been adopted internationally by the food industry.ď(NH&MRC NRMMC, 2004, NH&MRC, 2013).

This would seem a good path to follow for NSW EPA.

Environmental management plans are alluded to in the current guidelines but only briefly (NSW EPA, 1997) probably reflecting EMSs themselves being a relative new introduction at the time of these guidelinesôrelease. Since then though there has been much greater rollout of the EMS standards which NSW EPA itself promotes e.g. :

- NSW EPA (2016b);
- NSW EPA (2015).

These two documents for example provide advice on licensing of pollution generating production and identify the ISO 14000 set of standards as being central. The first of these documents also provides a primary check list for organisations, which address the sorts of activities managed through an EMS and were spelt out in the previous biosolids guidelines e.g. record maintenance, legal requirements; as well as new ones such as detailing of corrective action and staff training. The second outlines the need for continual improvement.

The EMS documents appear to support holistic biosolids management overall being based on a comprehensive application of the ISO 14000 standard. Thus when developing new biosolids management guides the range of new support documents in this standard e.g. (ISO, 2011, ISO, 2010, ISO, 2004b, ISO, 2004a) need to be scrutinised, and relevant heads consideration incorporated into any new guidelines. **The development of EMSs for biosolids beneficial reuse seems a logical next step and reflecting this, recommendations of EMS development in the guidelines**.

3.2. EMS concepts

For information of those unfamiliar with EMSs, **Figure 26** shows the general idea behind environmental management systems and the continual improvement. **Figure 27** shows a list of the basic activities this entails. It highlights how the 14000 standard emerged from the ISO 9000 standard set which in turn aims to support best practice production on any product (which biosolids are).

EMS are common already in the management of other organic wastes such as those developed for the livestock industry e.g. (McGahan and Tucker, 2003). **So it would seem a given that the new guidelines would mandate EMSs and ISO 9000 management systems for biosolids.**

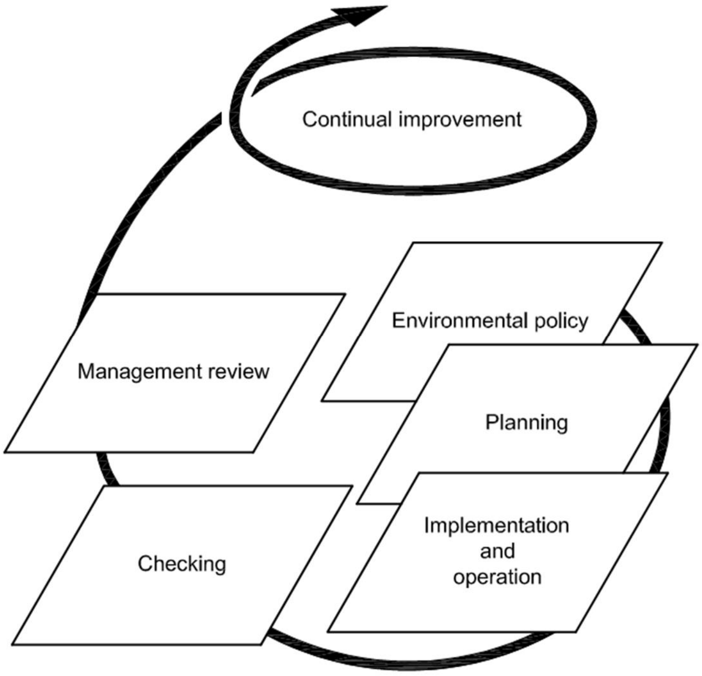

Figure 26. ISO 14000 Cycle of continuous improvement (ISO, 2004a)

ISO 14001:2004			ISO 9001:2000
Environmental management system requirements (title only)	4	4	Quality management system (title only)
General requirements	4.1	4.1	General requirements
Environmental policy	4.2	5.1	Management commitment
		5.3	Quality policy
		8.5.1	Continual improvement
Planning (title only)	4.3	5.4	Planning (title only)
Environmental aspects	4.3.1	5.2	Customer focus
		7.2.1	Determination of requirements related to the product
		7.2.2	Review of requirements related to the product
Legal and other requirements	4.3.2	5.2	Customer focus
		7.2.1	Determination of requirements related to the product
Objectives, targets and programme(s)	4.3.3	5.4.1	Quality objectives
		5.4.2	Quality management system planning
		8.5.1	Continual improvement
Implementation and operation (title only)	4.4	7	Product realization (title only)
Resources, roles, responsibility and authority	4.4.1	5.1	Management commitment
		5.5.1	Responsibility and authority
		5.5.2	Management representative
		6.1	Provision of resources
		6.3	Infrastructure
Competence, training and awareness	4.4.2	6.2.1	(Human resources) General
		6.2.2	Competence, awareness and training
Communication	4.4.3	5.5.3	Internal communication
		7.2.3	Customer communication
Documentation	4.4.4	4.2.1	(Documentation requirements) General
Control of documents	4.4.5	4.2.3	Control of documents
Operational control	4.4.6	7.1	Planning of product realization
		7.2.1	Determination of requirements related to the product
		7.2.2	Review of requirements related to the product
		7.3.1	Design and development planning
		7.3.2	Design and development inputs
		7.3.3	Design and development outputs
		7.3.4	Design and development review
		7.3.5	Design and development verification
		7.3.6	Design and development validation
		7.3.7	Control of design and development changes
		7.4.1	Purchasing process
		7.4.2	Purchasing information
		7.4.3	Verification of purchased product
		7.5.1	Control of production and service provision
		7.5.2	Validation of processes for production and service provision
		7.5.5	Preservation of product
Emergency preparedness and response	4.4.7	8.3	Control of nonconforming product
Checking (title only)	4.5	8	Measurement, analysis and improvement (title only)
Monitoring and measurement	4.5.1	7.6	Control of monitoring and measuring devices
		8.1	(measurement, analysis and improvement) General
		8.2.3	Monitoring and measurement of processes
		8.2.4	Monitoring and measurement of product
		8.4	Analysis of data
Evaluation of compliance	4.5.2	8.2.3	Monitoring and measurement of processes
		8.2.4	Monitoring and measurement of product
Nonconformity, corrective action and preventive action	4.5.3	8.3	Control of nonconforming product
		8.4	Analysis of data
		8.5.2	Corrective action
		8.5.3	Preventive action
Control of records	4.5.4	4.2.4	Control of records
Internal audit	4.5.5	8.2.2	Internal audit
Management review	4.6	5.1	Management committment
		5.6	Management review (title only)
		5.6.1	General
		5.6.2	Review input
		5.6.3	Review output
		8.5.1	Continual improvement

Figure 27. Key features of an ISO 14000 compliant environmental management system (ISO, 2004a)

3.3. The REQUAL model

If this best practice was adopted biosolids stakeholders might obtain benefit from the water industry via further route. This is the adaptation of the comprehensive and adaptable EMS advice/model REQUAL (Davison, 2010, Water Services Association of Australia, 2010). REQUAL was developed at the request of the Australian water industry to provide more specific operational guidance on how to design, manage and audit recycled water systems. It was based on the principles in the Recycled Water guideline (Environment Protection and Heritage Council, 2006) and a similar document developed for drinking water, AQUAL. This document was designed to identify key strategic tasks that organizations managing water were responsible for undertaking if they wished to comprehensively implement the guidelines, in short an overall management framework. WRC had an opportunity to examine REQUAL (Khan et al., 2010) after being requested by Willoughby Council (2013) to evaluate plans for a stormwater flood control + water recycling system. Reflecting this experience WRC considers there is much that could be transferred to biosolids management.

REQUAL itself is an on line database system reflecting industry and regulator consultation about what constitute best management practice which is designed to document management plans, be continually improved and for the information to be shared among recycled water managers. It is divided into (Davison, 2010):

- “12 Elements
    - (Major, high-level elements that comprise water quality management - taken from the guidelines reflecting what water risk management involves)
- 36 Components
    - (Subordinate components of the 12 elements. Too high a level to allow meaningful assessment.)
- 85 Actions
    - (Specific actions collectively comprising a component. First level in the hierarchy at which activity can be objectively assessed. Still too high for meaningful assessment, too general to enable consistent application within and across the industry).
- 195 Measures
    - (Specific to Requality, one or more measures is included under each action. The measures enable an assessment of if, and how well, a water quality management component or action is done by the organisation)”

These in turn reflect and so complement the recycled water guidelines (Environment Protection and Heritage Council, 2006).

In WRC's opinion this management and (self) auditing for recycled water schemes appears to be largely adaptable in principle if not totally transferable to biosolids management including odour management. To illustrate the potential, Table 32 reproduces the Elements, Components and Actions with the word Biosolids replacing Recycled water. It can be seen that none of the implied management activities is exceptionable.

Further though the REQUAL documents suggest the measures are specific to Requality the following random selection of 'Measures' demonstrates there is in this also little that needs alteration before it also could be applied to biosolids management:

- “The agency has planned and documented its operational monitoring.
- The agency has procedures that detail individual responsibilities and include communication and notification requirements.
- The agency has a process for selecting monitoring equipment on the basis of its ability to meet the accuracy, sensitivity and reliability required.
- The agency has a process for selecting appropriate suppliers for all its sewage and recycled water treatment chemicals to ensure that only approved chemicals are used.
- The agency undertakes the verification monitoring required for compliance with statutory monitoring of recycled water quality.

- For each recycled water system, the agency has identified the specific end use and all characteristics that need to be monitored to manage the risks associated with that end use.
- The agency has a process for recording all comments and complaints from users of recycled water and the actions undertaken by the agency in response to the complaints.
- The agency has procedures for the reporting of recycled water quality results to operators and senior executives, as well as externally if required.
- The agency has procedures for corrective responses to feedback from users. The procedures include clear definition of authorities and responsibilities.
- The agency has trained media liaison officers that are nominated as the responsible officers for interactions with the media during incidents and emergencies.
- The agency has developed a clear understanding of the definitions of incidents and emergencies.
- All agency employees and contractors involved in recycled water have participated in an awareness program for the recycled water quality management program.ò

A biosolids equivalent to REQUAL would provide a strategic level tool for integrating biosolids (risk) management activities across NSW and potentially nationally.

The main constraint on adapting this scheme to biosolids seems to be the shear scale of the management process demanded by the aim to achieve óbest practiceô That said the process has been put on line to make its use as efficient as possible and to evolve a resource that water managers can exploit. This idea seems also applicable to biosolids in principle and there is no clear reason why the whole REQUAL system could not be cloned for biosolids subject to the agreement of the intellectual property holders who include many of the same organisations as generate biosolids! The latter also means that the increasing recycled water management experience and other resources should be adaptable to biosolids management.

In respect to the logistics issue ISO 14000 can also probably help. ISO 14005 specifically advised on óPhased implementationô(ISO, 2010):

ñThere are many potential benefits to be gained by an organization from managing its environmental aspects. However, organizations can be deterred from applying a systematic approach to environmental management, if they perceive this as being an inflexible, limiting, bureaucratic or costly process. They can also be overwhelmed by the apparent size of the task.

The model outlined in this International Standard has been developed to help an organization to implement an EMS in a particular way, while growing the extent and scope of the system, through time, in line with the objectives of the organization and the resources available.ò

Table 32. Requal Environmental Management System ôElementsô and ôComponentsô(adapted from REQUAL as described by Davison, 2010, Water Services Association of Australia, 2010)

Element	Element Text	Component	Component Text	Action	Action Text
1	Commitment to responsible use and management of (biosolids) quality	1.1	Responsible use of (biosolids)	1.1.1	Involve agencies (i.e. stakeholders) with responsibilities and expertise in protection of public and environmental health.
				1.1.2	Ensure that design, management and regulation of (biosolids) schemes is undertaken by agencies and operators with sufficient expertise.
		1.2	Regulatory and formal Requirements	1.2.1	Identify and document all relevant regulatory and formal requirements.
				1.2.2	Identify governance of (biosolids)schemes for individual agencies, designers, installers, operators, maintainers, owners and users of (biosolids).
				1.2.3	Ensure that responsibilities are understood and communicated to designers, installers, maintainers, operations employees, contractors and end users.
				1.2.4	Review requirements periodically, to reflect any changes.
		1.3	Partnerships and engagement of stakeholders (including the public)	1.3.1	Identify all agencies with responsibilities for water resources and use of (biosolids); regularly update the list of relevant agencies.
				1.3.2	Establish partnerships with agencies or organisations as necessary or where this will support the effective management of (biosolids)schemes.
				1.3.3	Identify all stakeholders (including the public) affecting, or affected by, decisions or activities related to the use of (biosolids).
				1.3.4	Engage users of (biosolids); ensure responsibilities are identified and understood.
				1.3.5	Develop appropriate mechanisms and documentation for stakeholder commitment and involvement.
		1.4	(Biosolids) policy	1.4.1	Develop a (biosolids) policy, endorsed by senior managers, to be implemented within an organisation or by participating agencies.
				1.4.2	Ensure that the policy is visible and is communicated, understood and implemented by employees and contractors.
2	Assessment of the (biosolids) System	2.1	Intended uses and source of (biosolids)	2.1.1	Identify source of (biosolids).
				2.1.2	Identify intended uses, routes of exposure, receiving environments, endpoints and effects.
				2.1.3	Consider inadvertent or unauthorised uses.
		2.2	(biosolids) system analysis	2.2.1	Assemble pertinent information and document key characteristics of the (biosolids) system to be considered.
				2.2.2	Assemble a team with appropriate knowledge and expertise.
				2.2.3	Construct a flow diagram of the (biosolids) system from the source to the application or receiving environments.

Element	Element Text	Component	Component Text	Action	Action Text
				2.2.4	Periodically review the (biosolids) system analysis.
		2.3	Assessment of (biosolids) data	2.3.1	Assemble historical data about sewage (and biosolids), as well as data from treatment plants and of (biosolids) supplied to users; identify gaps and assess reliability of data.
				2.3.2	Assess data (using tools such as control charts and trends analysis), to identify trends and potential problems.
		2.4	Hazard identification and risk assessment	2.4.1	Define the approach to hazard identification and risk assessment, considering both public and ecological health.
				2.4.2	Periodically review and update the hazard identification and risk assessment to incorporate any changes.
				2.4.3	Identify and document hazards and hazardous events for each component of the (biosolids) system.
				2.4.4	Estimate the level of risk for each identified hazard or hazardous event.
				2.4.5	Consider inadvertent and unauthorised use or discharge.
				2.4.6	Determine significant risks and document priorities for risk management.
				2.4.7	Evaluate the major sources of uncertainty associated with each hazard and hazardous event and consider actions to reduce uncertainty.
3	Preventive Measures for (biosolids)Management	3.1	Preventive Measures and multiple barriers	3.1.1	Identify existing preventive Measures system-wide for each significant hazard or hazardous event, and estimate the residual risk.
				3.1.2	Identify alternative or additional preventive Measures that are required to ensure risks are reduced to acceptable levels.
				3.1.3	Document the preventive Measures and strategies, addressing each significant risk.
		3.2	Critical Control Points	3.2.1	Assess preventive Measures throughout the recycled water system to identify critical control points.
				3.2.2	Establish mechanisms for operational control.
				3.2.3	Document the critical control points, critical limits and target criteria.
4	Operational Procedures and Process Control	4.1	Operational procedures	4.1.1	Identify procedures required for all processes and activities applied within the whole recycled water system (source to use).
				4.1.2	Document all procedures and compile into an operations manual.
		4.2	Operational monitoring	4.2.1	Develop monitoring protocols for operational performance of the recycled water supply system, including the selection of operational parameters and criteria, and the routine analysis of results.
				4.2.2	Document monitoring protocols into an operational monitoring plan.
		4.3	Operational corrections	4.3.1	Establish and document procedures for corrective action where operational parameters are not met.
				4.3.2	Establish rapid communication systems to deal with unexpected events.
		4.4	Equipment	4.4.1	Ensure that equipment performs adequately and provides sufficient flexibility and process

Element	Element Text	Component	Component Text	Action	Action Text
			capability and maintenance		control.
				4.4.2	Establish a program for regular inspection and maintenance of all equipment, including monitoring equipment.
		4.5	Materials and chemicals	4.5.1	Ensure that only approved materials and chemicals are used.
				4.5.2	Establish documented procedures for evaluating chemicals, materials and suppliers.
5	Verification of (biosolids) Quality and Environmental Performance	5.1	(biosolids) quality monitoring	5.1.1	Determine the characteristics to be monitored.
				5.1.2	Determine the points at which monitoring will be undertaken.
				5.1.3	Determine the frequency of monitoring.
		5.2	Application site and receiving environment monitoring	5.2.1	Determine the characteristics to be monitored and the points at which monitoring will be undertaken.
		5.3	Documentation and reliability	5.3.1	Establish and document a sampling plan for each characteristic, including the location and frequency of sampling, ensuring that monitoring data is representative and reliable.
		5.4	Satisfaction of users of (biosolids)	5.4.1	Establish an inquiry and response program for users of (biosolids), including appropriate training of people responsible for the program.
		5.5	Short-term evaluation of results	5.5.1	Establish procedures for the short-term review of monitoring data and satisfaction of users of (biosolids).
				5.5.2	Develop reporting mechanisms internally and externally, where required.
		5.6	Corrective responses	5.6.1	Establish and document procedures for corrective responses to nonconformance or feedback from users of (biosolids).
				5.6.2	Establish rapid communication systems to deal with unexpected events.
6	Management of incidents and emergencies	6.1	Communication	6.1.1	Define communication protocols with the involvement of relevant agencies and prepare a contact list of key people, agencies and stakeholders.
				6.1.2	Develop a public and media communications strategy.
		6.2	Incident and emergency response protocols	6.2.1	Define potential incidents and emergencies and document procedures and response plans with the involvement of relevant agencies.
				6.2.2	Train employees and regularly test emergency response plans.
				6.2.3	Investigate any incidents or emergencies and revise protocols as necessary.
7	Operator, Contractor and End User Awareness	7.1	Operator, contractor and end user awareness and involvement	7.1.1	Develop mechanisms and communication procedures to increase operator, contractor and end user awareness of, and participation in, (biosolids) quality management and environmental protection.

Element	Element Text	Component	Component Text	Action	Action Text
	and Training	7.2	Operator, contractor and end user training	7.2.1	Ensure that operators, contractors and end users maintain the appropriate experience and qualifications.
				7.2.2	Identify training needs and ensure resources are available to support training programs.
				7.2.3	Document training and maintain records of all training sessions.
8	Community involvement and awareness	8.1	Consultation with users of (biosolids) and the community	8.1.1	Assess requirements for effective involvement of users of (biosolids)and the community.
				8.1.2	Develop a comprehensive strategy for consultation.
		8.2	Communication and education	8.2.1	Develop an active two-way communication program to inform users of (biosolids) and promote awareness of (biosolids) quality issues.
				8.2.2	Provide information on the impacts of unauthorised use.
				8.2.3	Provide information on the benefits of (biosolids) use.
9	Validation, Research and Development	9.1	Validation of processes	9.1.1	Validate processes and procedures to ensure they control hazards effectively.
				9.1.2	Revalidate processes when variations in conditions occur.
		9.2	Design of equipment	9.2.1	Validate the design of new equipment and infrastructure to ensure continuing reliability.
		9.3	Investigative studies and research monitoring	9.3.1	Establish programs to increase understanding of the recycled water supply system, and use this information to improve management of the (biosolids) supply system.
10	Documentation and reporting	10.1	Management of documentation and records	10.1.1	Document information pertinent to all aspects of recycled water quality management, and develop a document-control system to ensure current versions are in use.
				10.1.2	Establish a records-management system and ensure that employees are trained to complete records.
				10.1.3	Periodically review documentation and revise as necessary.
		10.2	Reporting	10.2.1	Establish procedures for effective internal and external reporting.
				10.2.2	Produce an annual report aimed at users of (biosolids), regulatory authorities and stakeholders.
11	Evaluation and audit	11.1	Long-term evaluation of results	11.1.1	Collect and evaluate long-term data to assess performance and identify problems.
				11.1.2	Document and report results.
		11.2	Audit of (biosolids) quality management	11.2.1	Establish processes for internal and external audits.
				11.2.2	Document and communicate audit results.
12	Review and	12.1	Review by	12.1.1	Senior managers review the effectiveness of the management system and evaluate the need for

Element	Element Text	Component	Component Text	Action	Action Text
	continuous improvement		senior managers		change.
		12.2	(biosolids) quality management improvement plan	12.2.1	Develop a (biosolids) quality management improvement plan.
				12.2.2	Ensure that the plan is communicated and implemented, and that improvements are monitored for effectiveness.

4. Appendix 4 - Next strategic steps in the integration of odour, stability and vermin assessment into new EMS and risk based biosolids management focused guidelines

4.1. Guidelines and resources for integration of odour management.

In the two previous Appendices various guidelines and standards were reviewed which potentially also support integration of current knowledge of biosolids with monitoring and management systems and harmonization of odour management with biosolids pathogen and toxic chemical assessment in the new biosolids guidelines and with comparable water and environmental risk management tools more generally.

The following list summarises key integration considerations identified, which biosolids guideline development could incorporate.

1. Use of enHealth Environmental Risk Assessment framework especially exposure assessment?:
    a. This scheme seems directly and largely applicable to odour with some minor adaptation.
    b. The odour ERA should cover biosolids production, transport and impacts of beneficial reuse.
2. Assembly of default values for scoping biosolid systems based on literature?:
    a. E.g.
        i. Odourants and characteristics of stabilised and unstabilised biosolids;
        ii. Odours arising from processed biosolids destabilization;
        iii. An updated list of stabilising technologies ;
        iv. characteristics of stabilized biosolids especially those amendable to monitoring;
        v. documentation of hazardous events and their impact including likelihood and consequence;
        vi. limits of soil assimilative capacity;
        vii. model default settings.
    b. When designing environmental risk assessment, recycled water, and drinking water management scheme one of the most useful features of these guidelines is the assembly of standard consensus information (e.g. EnHealth Council, 2012a, NH&MRC, 2013, Environment Protection and Heritage Council, 2006). These provide models for data on odours and biosolids that could be assembled;

   c. If such data is assembled properly it would provide a common, and effectively integrating, point of reference for prospective biosolids schemes so that the viability of management strategies can be assessed early on.
   d. Even draft sets of standard inputs based on industry committee expert opinion would be useful as was the case with the recycled water guidelines.
3. Use of national water quality guideline style consultation?:
   a. The Australian environmental water protection guidelines (ANZECC and ARMCANZ, 2000) appear to provide a good guide for the initial risk management integrating step of widespread stakeholder and community consultation.
   b. These guidelines also highlight the potential use of œEnvironmental Valuesô The latter seems particularly important in grounding what is desired in the way of odours and in turn clarifies what needs to be managed in addition to current odour unit based regulations.
4. Use of ISO 31010 tools, and Bayes nets and other models;
   a. ISO 31010 effectively provides another integrating framework which sanctions useful secondary risk modelling beyond ERA. ERA is probably suited to whole of system understanding while other tools seem suited to other biosolids management tasks as illustrated by the discussion of FTA which appears ideally suited for gaining a better understanding of, and prioritizing, hazardous events, and how to minimise their occurrence and impact.
   b. Bayes Nets and other models provide a natural way of integrating different biosolids information and identifying what monitoring is more useful than others.
   c. Bayes Net construction and use best practice appears to offer a way of undertaking virtually all major forms of risk assessment currently identified by the ISO and Standards Australia.

4.2. Stabilization

The concept of stabilization appears to be a vexed one. Review of the management literature suggests two options:

1. Frame stabilization as a conceptual Environmental Value but not a specific state;
2. And/or alternatively :
   a. View biosolids as a labile material comparable to food which along the field to fork is maintained in a metastable state with causes no odour offence provides processing, storage and transport are appropriate;

b. View stability as not a single concept but the preferred state of the biosolids at each point along the biosolids production/processing/transport/storage/beneficial reuse chain;
c. óStableô biosolids be defined as biosolids being in their target state at each critical control point along the management/reuse train.
d. View an unstable product as one where there is failure (e.g. excessive odour) are determined by Fault Tree Analysis or other scenario analysis where indicators of critical Environmental Values are no longer within control limits.

4.3. Vermin and Vectors

Vermin and vector management theory is still conceptual. So new research is needed, if only desktop in the first instance, to assess its significance, capacity for spreading pathogens to identify critical control points, appropriate indicators and benchmarks (e.g. fly density) and from there whether an experimental program is wanted.

Conceptually vermin and vector management comes in part under pathogen ERA. However it is not clear at this point what risk is posed by biosolids whose production train is operating nominally. The latter needs to be understood as well.

4.4. Guideline design to incorporate EMS and risk management

As evidenced by the variety of food and water guidelines, there are a range of possible formats which could be used to construct new biosolids guidelines and incorporate risk management and environmental management principles. The contents of such guidelines need to be developed by EPA in discussion with stakeholders. A possible shortcut would be to adapt the format and resources of one of the latest guidelines already developed with EMS and risk management in mind in effect learning from the discussions by experts in these related fields.

The latest recently updated version of the Australian Drinking Water Guidelines (NH&MRC, 2013) is notable in that it may provide a model which addresses the above needs. Major features of these guidelines are as follows:

1. Introduction including guiding principles (including discussion of centrality of risk management) ;
2. Part 1 covering the management of drinking water divided into 3 framework chapters covering óOverviewô (including identification of overlap between ISO 9000 management systems actions and HACCP based risk management), (EMS type) óElementsô and small supplies ;
3. Part 2 describing separately key water quality attributes under the headings microbial, physicochemical and radiological, and treatment chemicals;

4. Part 3 describing monitoring including the different types of monitoring and their purposes and what to monitor for;
5. Part 4 compiling óinformation sheetsô on disinfection, sampling and statistics
6. Part 5 on ófact sheetsô on microbes, physical and chemical features of water, and treatment chemicals
7. Appendices providing useful information on HACCP and risk assessment, further sources of information, the national water management strategy and the process by which the guidelines were developed.
8. A glossary

These guidelines comprehensively incorporate both EMS and risk management concepts, provide conceptual and operational management frameworks, reflect Australian conditions and have been in effect field tested already. WRC suggests EPA and the biosolids management industry could do worse than to ócloneô this guideline format and such resources in it as are applicable e.g. EMS principles. It is particularly noteworthy that these updated guidelines clearly recognise the special category of small water supply operations where resources are limited.