Methods to assess sustainability of sludge management

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INTRODUCTION
Sustainability and sustainable development are important concepts, however also concepts of which there are currently no full consensus. Aspects of sustainability for which there are almost full consensus are for example that it has three main aspects: environmental, social and economic sustainability. Another important aspect is the intergenerational equity, expressed by the famous World Commission on Environment and Development (WCED, 1987) as: "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". The three aspects–environmental, social and economic sustainability–is often referred to as the three pillars of sustainability or the "triple-bottom-line" (see e.g. Elliott, 2012). There are many factors to consider regarding sustainability. Crucial is our ability to assess sustainability, or assess our position in relation to the sustainability goals we want to achieve. Indicators of sustainability are important. In this paper we will look in the toolbox available to assess sustainability and sustainable development for wastewater sludge management.

METHODS
Literature studies, mainly in the databases ScienceDirect, Springer Link and Google Scholar.

RESULTS
Below indicators and assessment methods are presented. It turns out that there is no strict border between indicators and assessment methods, rather a circular continuum from indicators, indicators in frameworks, assessment methods, and indicators produced by assessment methods (Grönlund, 2014).

Indicators of sustainable wastewater treatment
Sustainability indicators have been frequently processed in the literature (for a good review, see Lundin, 2003). However, indicators directly addressing the sustainability of the sludge has not been possible to identify in this study. Indicators for sustainable wastewater treatment, though, have been used. Examples of wastewater system indicators connected to frameworks are the Sustainable Development Records (SDR) developed by Nilsson and Bergström (1995). OECD (1998) developed the framework Pressure-State-Response (PSR). The socio-ecological principles or conditions (Azar *et al.*, 1996; Holmberg *et al.*, 1996) can also be used as indicators. An example of a framework formalized as a modeling tool is the ORWARE model (Dalemo *et al.*, 1997; Dalemo *et al.*, 1998), which includes 43 indicators related to chemical compounds, such as BOD, nutrients, metals, and solids. The model was developed for evaluation of the environmental impact of waste management in different geographical areas, especially focusing on the return of nutrients to arable land. Lundin (2003) pointed out an interesting development path for wastewater related sustainable development indicators giving the example from Bossel (1997) of a systems analytical framework. To overcome the risk of specific expertise bias Bossel (1997) focused on the subsystems relation and contribution to the overall system, or the goals that are desirable for the society. Bossel's (1997) attempt suggested over 200 indicators, of which many were difficult to collect data for. Lundin (2003) found that "…the approach is interesting in that it starts by addressing the question of human needs and how different sectors can contribute to Sustainable Development." In the wastewater sector there has been some frameworks developed for sustainability indicators. Among them a SDR type system (see above) called the METRON project (Kallis and Coccossis, 2000) were developed for European metropolitan areas. Two similar projects have been developed, in Sweden,

“Sustainable Urban Water Management” (Hellström *et al.*, 1999; Malmqvist *et al.*, 2006), and in Great Britain, the SWARD project, “Sustainable Water Industry Asset Resources Decisions” (Ashley *et al.*, 2004; Ashley and Hopkinson, 2002; Foxon *et al.*, 2002).

Assessment methods

There is a whole set of tools available in the so called environmental assessment toolbox. A good overview were given by Wrisberg *et al.* (2002). In this section a set of tools are shortly presented: LCA, Exergy analysis, Economic analysis, Emergy analysis, and Environmental Risk Assessments.

Life cycle assessment (LCA)

LCA is a common assessment method for wastewater treatment, see Balkema *et al.* (2002) and Corominas *et al.* (2013) for overviews. The main application for LCA is to assess different environmental impacts during a product’s lifetime, for which it produces an inventory of environmental aspects based on mass and energy balances. These environmental aspects are then categorized in impact categories, such as global warming potential, depletion of resources, ozone depletion, acidification, ecotoxicity, eutrophication, landscape degradation, etc. These categories can be normalized and weighted against each other for a final decision support for which choice is the best from an environmental point of view. The main advantages of LCA is that it is well-described and standardized (ISO 14040, 2006) and that it can be applied to a wide range of products and services including wastewater treatment. The drawbacks of LCA is that the assessment of a complete life cycle requires a large quantity of data, and that it limits itself to a restricted set of technical and environmental aspects meaning it must be complemented for a full sustainability assessment.

Yoshida *et al.* (2013) compared 35 LCAs of sewage sludge, and concluded that the outcomes were not easy to compare. This since the “…results of LCA are, in principle, unique to the goal and scope of each study, reflecting its local conditions and comparison between different LCAs is not intended.” They found “…large discrepancies … in the selection of the environmental emissions to be included and how they were estimated in the analysis.“ Yoshida *et al.* (2013), regarding the key technological assumptions, recommended creating “…a common platform for documenting the assumptions, and improve the reproducibility and consistency of the studies.” They also highlighted the need to be clear about the choice of modelling approach.

Exergy analysis

The main advantage of exergy analysis is that the whole assessment is based on a single quantifiable indicator: exergy (Balkema *et al.*, 2002). This advantage is also its limiting factor, since exergy analysis only measures the efficiency of processes but has no assessment of different environmental impacts. Hellström (1997, 1998, 1999, 2003) used exergy analysis and concluded e.g. that if nitrogen removal is considered important urine separation systems are interesting alternatives. He also highlighted the large flows of exergy following the handling of organic matter, thereby providing an opportunity to retain exergy through methane production.

Ptasinski *et al.* (2002) investigated a new method of sewage sludge treatment “…by preserving the chemical exergy present in the sludge and transforming it into a chemical one—methanol.” Based on exergy analysis they claimed that this method contributes “…more than traditional methods to the sustainable technology by achieving a higher rational efficiency of sludge processing.” Bennamoun *et al.* (2016) used exergy analysis to find the optimum drying conditions for sewage sludge. Kalinci *et al.* (2011) used exergy analysis to show the benefits of incineration of sewage sludge by plasma gasification, and Fang *et al.* (2012) used the method to optimize a sewage sludge and coal co-combustion power generating system.

Economic analysis

Economy has two main branches in the environmental context. The dominating bransch, environmental economics, use a single indicator, where all aspects of sustainability are expressed in monetary terms (called internalization into the economic assessment). The main environmental economic tools are cost-benefit analysis, life cycle costing, and total cost assessment (Balkema *et al.*, 2002). According to environmental economic theory (based on neoclassical economic theory), all kinds of costs and benefits can be valuated and included. However, financial costs and benefits are often the only aspects included. This since most environmental and social costs is complicated to quantify.

In Cost-Benefit Analysis (CBA) the relevant costs and benefits are identified. Where no functioning market mechanism are in place, they are estimated with various methods such as contingent markets, travel costs, replacement costs etc. The costs and benefits are summed up and compared for the examined alternatives. Cost-effectiveness analysis is a type of CBA where the benefits are set fixed, similar to a functional unit in LCA. For example Birol *et al.* (2010), Ko *et al.* (2004), and Molinos-Senante *et al.* (2010) evaluated wastewater treatment systems with CBA. From a sludge perspective Hosseini Koupaie *et al.* (2014) investigated the feasibility of anaerobic co-digestion of two juice-based beverage industrial wastes, screen cake and thickened waste activated sludge, along with municipal sludge cake. The CBA revealed that the costs could be significantly decreased using a co-digester rather than two separate digesters. Nadal *et al.* (2009) used CBA to investigate the use of sewage sludge as an alternative fuel in a clinker kiln in Catalonia, Spain. Gretzschel *et al.* (2014) used CBA to investigate if a wastewater treatment plant (10,000-50,000 p.e.) using aerobic stabilisation should be converted to sludge digestion instead, in order to utilize the energy resource in the organic material. They found that this was beneficial for plants above 7,500 p.e. if the energy and operation costs increased with 5%. Parravicini *et al.* (2008) used CBA to investigate if post-aeration of anaerobically digested sewage sludge for advanced COD and nitrogen removal was efficient. The CBA showed that post-aeration of the digested sludge resulted in an increase of total annual costs for wastewater treatment of less than 1%.

If CBA or cost-effectiveness analysis is applied in a life cycle perspective it is called Life Cycle Costing (LCC) (Wrisberg *et al.*, 2002). The weakest part in LCC is the valuation of emission and other costs far out in the life cycle chain. For example Lim *et al.* (2008) used LCC to investigate the environmental and economic feasibility of a wastewater treatment network system. No articles with specific focus on sludge with a LCC approach were found in this investigation.

A second, minor branch of economy called ecological economy, is a diverse approach but with a common feature of not trying to internalize all costs and benefits in monetary terms. Rather different types of social and ecological costs keep their integrity in their original units (Grönlund *et al.*, 2009). The ecological economics approach can be said to rather "internalize" indicators for decision support from other methods as LCA, energy measures, or toxicity measures. Conversion to a single indicator exists, but then rather use different types of point systems than money. In the journal Ecological Economics four papers were found to include the word "sludge" in abstract or key words. Typically they were not using the same methodological approach (Gilbert and Feenstra, 1994; Günther, 1997; Nakamura, 1999; Lin, 2009).

Emergy analysis

Emergy analysis has during the last decades become a more and more popular method. It has a holistic approach with its basis in systems science and thermodynamics. The method has gain interest since it includes energy and material flows, but also economic flows within the same theoretical framework (Odum, 1983, 1994, 1996). This is an unusual position in the sustainability assessment toolbox (shared only with the Extended exergy approach, Sciubba, 2003). The method is still in a young phase and has met criticism from both natural scientists (e.g. Hau and Bakshi, 2004) and economists (e.g. Hornborg, 1998). In the ecological engineering branch of the wastewater treatment field emergy analysis has been popular, which is not surprisingly since the field has its roots in systems ecology with H.T. Odum as one of the major pioneers in the 1960s (Mitsch and Jorgensen, 1989; Odum, 1983).

Björklund *et al.* (2001) used emergy analysis to evaluate the use of environmental resources for wastewater treatment in a Swedish town (10,000 p.e). Among other things their study indicated that the resource requirements from the economy in the production of electricity by the digestion of sewage sludge was about two times higher than the total resource use for generation of the average electricity mix used by the town. They, therefore, concluded that it would be more resource-efficient to purchase the electricity on the Swedish distribution net, if the only reason to digest the sludge were to produce electricity. Accordingly, they concluded, the economic rationale were low in resource terms of producing biomass to digest just to increase the energy production at the wastewater treatment plant. Liu *et al.* (2015) investigated possibilities to reduce greenhouse gas emissions by using sewage sludge in clinker production. The results showed that the Emergy Yield Ratio dropped significantly, suggesting that polluting emissions greatly increase the system's demand for additional resources from outside to repair damage and replace lost natural and human-made capital (the latter amounting to about 10% of the total emergy investment).

Environmental Risk Assessment (ERA)

Environmental Risk Assessment (ERA) examines the risk that threatens ecosystems and society related to technology, processes or substances in either a qualitative or quantitative way (Wrisberg *et al.*, 2002). Risk assessments has a wide variation in scope and application. ERA investigations for wastewater has been performed by e.g. Escher *et al.* (2011), Ginebreda *et al.* (2010), Gros *et al.* (2010), Hernando *et al.* (2006), and Verlicchi *et al.* (2012).

DISCUSSION

Among the approaches available it can be seen that no method or indicator set in itself is strong enough to assess sustainability on its own. Rather they have different strengths and weaknesses. LCA for example has its strength in comparing different alternatives, while Emergy Analysis (and Ecological Footprints, Wackernagel and Rees, 1995) can add the dimension of what is good enough. Economic analysis can be good or weak depending on how well it can cover the so called externalities of environmental and social costs. Environmental Risk Assessment is to some extent included in the LCA methodology, if that type of impact categories are chosen.

Sustainability is difficult to assess on the scale of the sludge management. Rather it must be put in its larger context, first the level of the wastewater treatment solutions studied, but also as an embedded part of the society and always connected to the environmental systems via the effluent, the sludge itself or its ashes, or the fumes from incineration. What society delivers to the environmental systems via the wastewater treatment sector must be in a form that the environmental systems can handle and reuse, otherwise the risk of environmental problems will increase systematically. The economic and social sustainability aspects are highly interconnected, and from a systems point of view we cannot claim that a wastewater treatment solution is sustainable if it is coming out of a negotiation between contradicting environmental and economic demands. Rather a sustainable solution must ensure that the society and its economy are compatible and possible to embed in the environmental systems of nature, agriculture, forestry, aquaculture etc.

CONCLUSIONS

In this paper we have seen that in our toolbox of indicators and methods for assessing sustainability and sustainable development there is no consensus on an operational basis what tools to use. Rather the sustainability of sludge management and wastewater treatment has been assessed with very different methods and indicators, giving different answers. For management strategies this can be interpreted as that we know approximately in what rough direction we must go, but we do not have a precise roadmap. The current sustainability discussion in the wastewater treatment sector, including its sludge management, is often characterized by the practical solution of increasing sustainability by focusing on reducing obvious non-sustainability.

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