Chapter 2
Global Wastewater and Sludge Production, Treatment and Use

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Abstract Cities produce large amounts and very diverse types of waste including wastewater. The quality of these wastes depends on their source, the way in which they are collected and the treatment they receive. The final fate of these wastes is also very diverse. To better understand these systems this chapter provides definitions and reuse typologies and describes common reuse patterns and their driving factors. The chapter also shows that, while the prospects for resource recovery from wastewater and sludge are promising the potential is still largely untapped, except in the informal sector. The resources embedded in the approximately 330 km^3/year of municipal wastewater that are globally generated would be theoretically enough to irrigate and fertilize millions of hectares of crops and to produce biogas to supply energy for millions of households. However, only a tiny proportion of these wastes is currently treated, and the portion which is safely reused is significantly smaller than the existing direct and especially indirect use of untreated wastewater, which are posing significant potential health risks. The chapter ends with a call for standardized data collection and reporting efforts across the formal and informal reuse sectors to provide more reliable and updated information on the wastewater and sludge cycles, essential to develop proper diagnosis and effective policies for the safe and productive use of these resources.

Keywords Global wastewater production · Treatment options · Sludge production · Water reuse patterns

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2.1 Introduction

The worlds' population is increasing and concentrating in urban centres. This trend is particularly intense in developing countries, where an additional 2.1 billion people are expected to be living in cities by 2030 (United Nations 2012). These cities produce billions of tons of waste every year, including sludge and wastewater. The fate of these wastes is very different depending on the local context: they can be collected or not, treated or not and finally used directly, indirectly or end without beneficial use. In literature, data on these waste streams is scarce and scattered and comprehensive reviews and assessments at global level are missing, with only few and partial exceptions. Nevertheless, recent efforts from global organizations such as FAO/IWMI through AQUASTAT, UN-Habitat (2008) and the Global Water Intelligence (GWI 2014) allow to renew these assessments and provide a more updated review.

Municipal wastewater and sludge contain valuable resources such as water, organic matter, energy, and nutrients (e.g. nitrogen and phosphorus) which can be recovered for many and very diverse economic, social and environmental purposes. However, and as a consequence of the deficient global data on these waste flows, the total amount of resources that is recovered for beneficial uses has not been well quantified so far.

This chapter offers a systematic and synthesized review of urban wastewater and sludge flows and provides definitions and key figures to better understand the subsequent chapters of this book. The chapter also tries to look at the dimension of valuable resources embedded in waste streams and the extent to which these resources are so far being recovered for beneficial uses, making wastewater and fecal sludge economic assets. Where data are weak or scarce, the causes of such data gaps are discussed.

2.2 Typology of Reuse and Definitions

Wastewater use can range from the formal use of ultrapure recycled water for advanced industrial purposes to the informal use of untreated and raw wastewater for vegetable production in a peri-urban area. The diversity of cases is as large as the diversity of types of wastewater and sludge, types of reuse and types of users (Box 2.1 and 2.2).

Box 2.1: Types of Wastewater Treatment

Before being treated, sewage usually goes through *pre-treatment* to remove grit, grease and gross solids that could hinder subsequent treatment stages.

Later, *primary treatment* aims to settle and remove suspended solids, both organic and inorganic. The most common primary treatments are primary settlers, septic and imhoff tanks.

In *secondary treatment* soluble biodegradable organics are degraded and removed by bacteria and protozoa through (aerobic or anaerobic) biological processes. Typical secondary treatments include aerated lagoons, activated sludge, trickling filters, oxidation ditches and other extensive processes such as constructed wetlands.

Tertiary treatment aims at effluent polishing before being discharged or reused and can consist the removal of nutrients (mainly nitrogen and phosphorous), toxic compounds, residual suspended matter, or microorganisms (disinfection with chlorine, ozone, ultraviolet radiation or others). Nevertheless this third stage/level is rarely employed in low-income countries. Tertiary treatment process can include membrane filtration (micro-, nano-, ultra- and reverse osmosis), infiltration/percolation, activated carbon, disinfection (chlorination, ozone, UV).

Finally, *water reclamation* refers to the treatment of wastewater to make it suitable for beneficial use with no or minimal risk.

2.2.1 Types of Wastewater, Treatment and Uses

Wastewater can be defined as 'used water discharged from homes, businesses, industry, cities and agriculture' (Asano et al 2007). According to this definition there are as many types of wastewater as water uses (e.g. urban wastewater, industrial wastewater, or agricultural wastewater). Where the wastewater is collected in a municipal piped system (sewerage) it is also called sewage. The term 'wastewater' as used in this book is basically synonymous with urban (or municipal) wastewater which is usually a combination of one or more of the following:

- Domestic effluent consisting of blackwater (from toilets) and greywater (from kitchens and bathing)
- Water from commercial establishments and institutions, including hospitals
- Industrial effluent where present
- Stormwater and other urban runoff

Wastewater can be collected or not, treated or not, and finally used directly or discharged to a water body, and then, be either reused indirectly downstream or support environmental flow (Fig. 2.1).

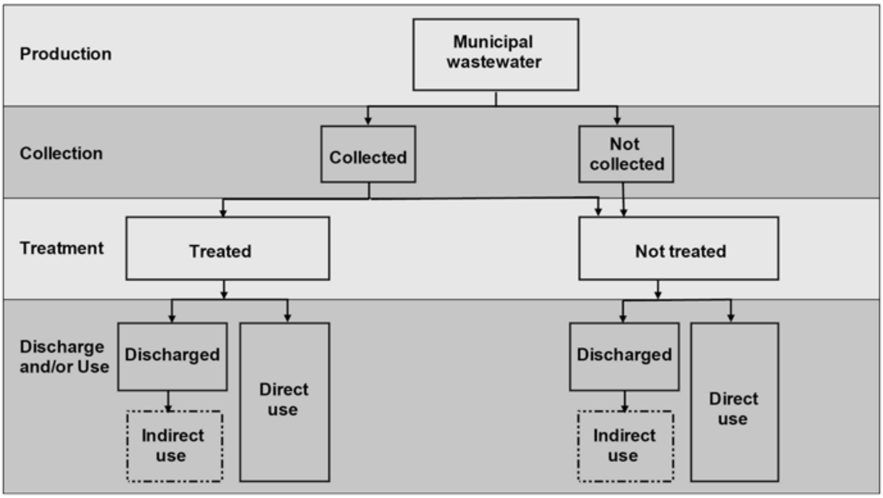

Fig. 2.1 Municipal wastewater chain, from production to use. (Source: Adapted from Mateo-Sagasta and Salian 2012)

Box 2.2: Types and Examples of (Treated or Untreated) Wastewater Usages (GWI 2009):

Agricultural Irrigation: Crop Irrigation, Commercial Nurseries

Landscape Irrigation: Parks, School Yards, Freeway Medians, Golf Course, Cemeteries, Greenbelts, Residential

Industrial Recycling and Reuse: Cooling Water, Boiler Feed, Process Water, Heavy Construction

Groundwater Recharge: Groundwater Replenishment, Saltwater Intrusion Control, Subsidence Control

Recreational/Environmental Uses: Lakes and Ponds, Marsh Enhancement, Stream-Flow Augmentation, Fisheries, Snowmaking

Non-potable Urban Uses: Fire Protection, Air Conditioning, Toilet Flushing

Potable reuse: Blending in Water Supply Reservoirs, Pipe-To-Pipe Water Supply

The direct use of wastewater implies that treated or untreated wastewater is used for different purposes (such as crop production, aquaculture, forestry, industry, gardens, golf courses) with no or little prior dilution. When it is used indirectly, the wastewater is first discharged into a water body where it undergoes dilution prior to use downstream (Fig. 2.2).

Finally reuse can be planned or unplanned. Planned use of wastewater refers to the deliberate and controlled use of raw or treated wastewater for example for

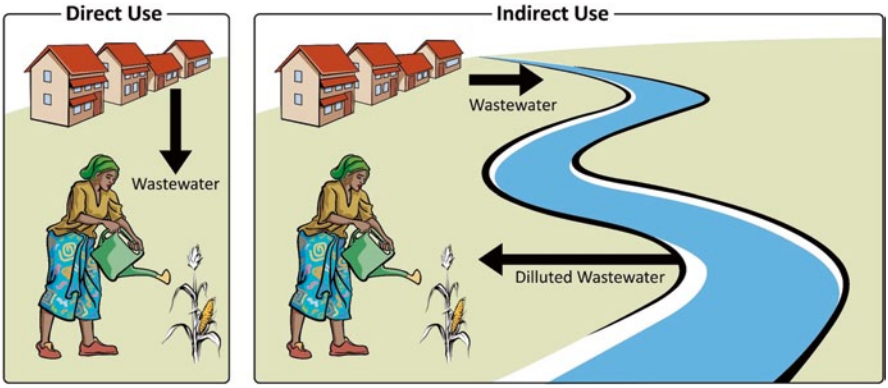

Fig. 2.2 Simplified example of direct and indirect reuse. (Source: Authors)

irrigation. Most indirect use, i.e. after dilution, occurs without planning. Aquifer recharge might be an exception (see also Chap. 9).

2.2.2 Types of Sludge, Treatment and Uses

Excreta which gets collected in a toilet remain either on-site (e.g. in a pit latrine or septic tank) or is transported off-site in sewer systems. When collected on-site, excreta is commonly called fecal sludge which is usually pumped and transported through trucks to fecal sludge treatment ponds or if there are no treatment facilities discharged untreated. The combination of sludge, scum and liquid pumped from septic tanks is called septage, although, many times the terms “septage” and “fecal sludge” are interchangeably used. Sewage treatment plants also produce sludge, called sewage sludge, when suspended solids are removed from the wastewater and when soluble organic substances are converted to bacterial biomass which also become part of the sludge (Fig. 2.3).

The characteristics of sludge depend on the origin and quantity of flushing water (public toilet, private toilet), its collection type (on-site, off-site) and subsequent treatment level, for example digestion (Table 2.1). Fresh and untreated sludge will have many pathogens, a high proportion of water, high biochemical oxygen demand (BOD) and is normally putrid and odorous. Nevertheless, sludge also contains essential nutrients for plants (e.g. nitrogen and phosphorus) and is potentially a very beneficial fertilizer. The organic carbon in the sludge, once stabilized, has also potential as a soil conditioner because it improves soil structure for plant roots, or can be transformed into energy through bio-digestion or incineration. As sewage may receive harmful pollutants (e.g. heavy metals, pharmaceuticals) from industries and other activities which may accumulate in its sludge, the sludge collected from

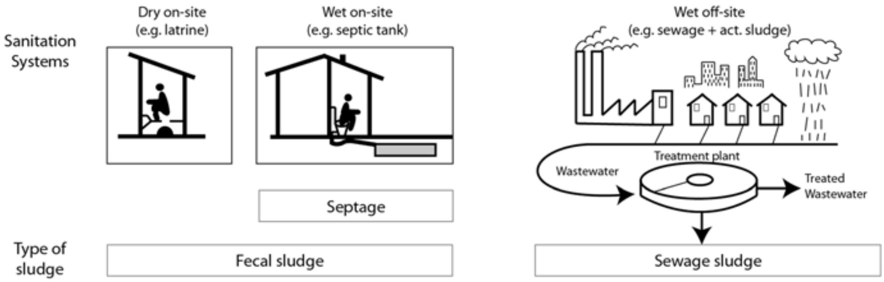

Fig. 2.3 Sludge types. (Source: Authors)

Table 2.1 Typical properties of untreated and digested sewage sludge. (Source: Metcalf and Eddy 2003, modified)

Item (% dry weight)	Untreated primary sludge		Digested primary sludge	
	Range	Typical	Range	Typical
Total dry solids	2–8	5	6–12	10
Volatile solids	60–80	65	30–60	40
N	1.5–4.0	2.5	1.6–6.0	3.0
P_2O_5	0.8–2.8	1.6	1.5–4.0	2.5
K_2O	0–1	0.4	0–3	1
pH	5–8	6	6.5–7.5	7

on-site systems is normally considered safer in view of reuse unless households use their toilets for general waste disposal.

The treatment required will be dependent on the initial characteristics of the sludge and its final use. The main purposes of treatment are to reduce the water content, BOD, pathogens and any bad odors. Options for sludge treatment include thickening, dewatering/drying as well as stabilization/composting (Strauss et al 2003; Koné et al 2010).

Water content in raw sludge is as high as 98 % which makes it unsuitable for composting and makes handling and transport difficult and costly. With sludge thickening in a sedimentation pond water content can be lowered up to 90 %. Dewatering and drying reduce the water content further so that the solid part of the sludge remains about 20 % (UNEP 2001). Dewatering is faster but requires energy to press-filter or centrifuge while drying takes more time (even weeks) but does not require energy as water is lost through evaporation and drainage.

Both aerobic and anaerobic processes can be used for sludge stabilization. Aerobic stabilization is typically done through composting at higher temperatures (55 °C) which imitates an accelerated natural process that takes place on a forest floor where the organic material (leaf litter, animal wastes) is broken down, resulting in an overall reduction of volume, or converted to more stable organic materials. In anaerobic stabilization, bacterial decomposition through anaerobic processes, reduces BOD in organic wastes and produces a mixture of methane and carbon dioxide gas (biogas).

Once properly treated, sewage sludge is called biosolids and if safe can be marketed for beneficial uses e.g. in landscaping. The application of biosolids on land can contribute to the generation of new soil, where there was virtually none, or increase the physical and chemical fertility of existing soils, thus reducing the need for other soil ameliorants (see Chap. 13).

Sludge can also be used for energy recovery, if sufficiently dry directly, through incineration or, indirectly, through anaerobic digestion, pyrolysis or gasification, which produce bio-fuels such as methane-rich biogas, bio-oil and syngas (Kalogo and Monteith 2012). Anaerobic digestion is the cheapest option as there is no energy input needed and the residual 'cake' can still be used as soil ameliorant. However, when sludge has high concentrations of heavy metals or persistent pollutants, anaerobic digestion would not be the best option as the resulting digested sludge would not be suitable for agricultural application. In these circumstances incineration, pyrolysis or gasification may be more suitable. A thorough analysis of options is provided in Chap. 12.

2.2.3 Reuse Types and Patterns

As outlined in Chap. 1, the increasing scarcity of water and fertilizers in many parts of the world is one of the motivations of wastewater use, be it treated or not. The physical, economic, social, regulatory and political environments greatly influence the type of wastewater use that takes place, resulting in very heterogeneous situations (Scheierling et al 2011; Raschid-Sally 2013). Yet, common reuse patterns can be identified for wastewater (Mateo-Sagasta and Burke 2010). Generally, in low income countries, where wastewater collection and treatment has limited coverage, wastewater and sludge tend to be used mostly informally, with no prior treatment, while in high income countries, with high health and environmental awareness, wastewater and sludge are generally treated, and their use is regulated and planned. While this does not look surprising, the magnitude of informal wastewater use which is probably ten times higher than formal reuse (Scott et al 2010) appears remarkable, as well as the limited data on the use of sludge.

Direct use of untreated wastewater occurs in low income settings where alternative water sources are scarce, i.e. usually in drier climates but also in wetter climates in the dry season. The reasons for such use can be lack or low quality of alternative water sources (e.g. groundwater salinity), or the unaffordable costs of accessing freshwater (e.g. costs of pumping). Although officially disapproved in most countries direct use of untreated wastewater takes place in many urban and peri-urban areas of the developing world (Raschid-Sally and Jayakody 2008; WHO 2006). The most common reuse form is in agriculture. For example, untreated wastewater is used on farms located downstream of many cities in Pakistan, because treated wastewater and groundwater are too saline for irrigation (Ensink et al 2002). In the semi-arid climate of the twin city of Hubli–Dharwad in Karnataka, India, farmers irrigate with untreated wastewater from open sewers (locally known as sewage nallas) and underground sewer pipes (Bradford et al 2002) because it is cheaper than using groundwater from boreholes, for which farmers have no capacity to pay. In other cases, such as Cochabamba in Bolivia, or Accra and Tamale in Ghana, farmers use wastewater from malfunctioning treatment plants or sewers, taking advantage of the already collected resource (Huibers et al 2004; Abdul-Ghaniyu et al 2002). In Haroonabad, Pakistan, and Hyderabad, India, wastewater is the only water flowing in irrigation canals in the dry season and at the tail-ends of irrigation schemes (Ensink 2006). In some extreme cases, farmers rupture or plug sewage lines to access the wastewater. This practice has been reported in Nairobi in Kenya, Bhaktapur in the Katmandu Valley in Nepal, and for example Dakar in Senegal (Hide et al 2001; Rutkowski et al 2007; Faruqui et al 2004). At Maili Saba in Kenya, as well as Addis Ababa in Ethiopia, farmers have removed sewage line inspection covers to block the sewer, causing raw sewage to rise up the manholes and flow out over the farm land (Hide et al 2001; own observation).

Indirect use of untreated wastewater is by far the most extensive type of use (Jimenez and Asano 2008; Keraita et al 2008; Scott et al 2010). It occurs in drier and wetter climates, when untreated wastewater is discharged into freshwater streams where it becomes diluted and is subsequently used—mostly unintentionally—by downstream users (e.g. farmers, households or industries). Untreated wastewater discharge occurs more frequently in low and middle income countries with little or no capacity for collecting and treating wastewater effectively. Additionally, the opportunity to sell crops into urban food markets encourages farmers to seek irrigation water in the city vicinity.

Several examples of indirect use of untreated wastewater have been reported in sub-Saharan Africa, Nepal, India, and around many cities in Brazil, Argentina, and Colombia, which lack adequate sanitation facilities (Keraita et al 2008; Jimenez 2008; Raschid-Sally and Jayakody 2008). In West Africa, there is extensive irrigation of vegetables in city vicinity with highly polluted water. Up to 90 % of vegetables consumed in the cities are grown within or near the same urban areas (Drechsel et al 2006).

Planned use of reclaimed water occurs more frequently in high income countries where the main motivation for water reclamation and reuse is water scarcity, although in many countries with no scarcity problems but with high environmental awareness, wastewater is also being reclaimed and used to preserve freshwater ecosystems. Reclaimed water can be used directly for many purposes such as agricultural irrigation, for city landscaping, golf courses, toilet flushing, washing of vehicles, groundwater recharge, and also as a source of potable water supply, like the case of Windhoek in Namibia testifies (Lahnsteiner et al 2013). Within industries wastewater may be purified to industrial standards and recycled within the system. In all of these cases reclaimed water is seen as vital resource, essentially for its "water" value (see also chap. 10). Planed use of reclaimed water is today a common pattern in countries of the Middle East and North Africa, Australia, the Mediterranean, and the United States of America (AQUASTAT 2014; Global Water Intelligence 2010). In all these cases, highly effective sanitation and treatment technology supports water reclamation, while the main challenge for reuse is public acceptability (see Chap. 5).

Informal use of untreated sludge. While sludge can be used on farm if safety precautions are followed, the enforcement of regulations (if they exist) is weak in many low-income countries. Although reuse is usually disapproved in such conditions, it can be a thriving business. As any use of untreated sludge happens in a very informal way, there are however only few data available. Many farmers consider sludge, even untreated, to be a valuable nutrient source similar to farmyard manure and prefer that septic trucks discharge their content onto their farms to use it after drying as fertilizer. This has been reported in West Africa and South Asia (Kvarnström et al 2012; Cofie et al 2005). The delivery of sludge from on-site sanitation facilities via septic trucks to farmers who pay for it is an interesting model of resource recovery if the on-farm treatment is able to reduce the obvious health risks (Keraita et al 2014; see also Chap. 13).

There can also be indirect reuse of sludge, but probably not in a planned way. Fact is that in many cities in developing countries, septage haulers empty waste into sewers, vacant land, landfill sites or water bodies, simply due to the lack of designated treatment facilities. When untreated sludge is discharged to water bodies it becomes diluted and might find its way back into the food chain where the water is used in farming.

Formal use of biosolids in agriculture is strictly regulated in developed countries but can be encouraged like in Michigan's biosolid and septage programs. Reuse is driven by the intention of closing nutrient loops to ensure that nutrients are returned to agricultural land to improve soil fertility while reducing the pressure on final deposal sites. Nevertheless, in many industrialized countries, there is a growing opposition to the use of biosolids in agriculture, due to concerns regarding the potential content of persistent and toxic pollutants such as heavy metals. In these countries energy recovery from sludge, mainly through bio-digestion and incineration, is gaining momentum.

2.3 Wastewater and Sludge Production and Treatment

2.3.1 Wastewater

Information describing current levels of wastewater generation and treatment is globally important for the post—2015 discussion as well as national policy makers, researchers, practitioners, and public institutions, to develop national policy and action plans aiming at wastewater treatment and productive use of wastewater (e.g. in agriculture, aquaculture, and agroforestry systems, or industry). Nevertheless this information is frequently not systematically monitored or not reported in many countries as stressed by Sato et al 2013, with a significant paucity of data on the rural sector.

In 2010, global annual domestic water withdrawals modeled by WaterGAP3 accounted for 390 km^3 (Flörke et al 2013) compared to 477 km^3 estimated time back by Shiklomanov 2000. The WaterGAP model further estimated a global production of wastewater in the domestic and manufacturing sectors of 450 km^3 in 2010, approximately 70 % (315 km^3) of which was accounted for by the domestic sector (Flörke et al 2013).

Empirical records compiled from a variety of sources for example by AQUASTAT and Sato et al 2013 suggest that globally more than 330 km^3 $year^{-1}$ of (mostly) municipal wastewater are produced. The countries in Table 2.2 alone, which account for more than 80% of the global urban population, produce an estimated volume of 261 km^3 of wastewater annually, and this is a conservative figure, as some of the national data appear outdated. Together, China, India, United States, Indonesia, Brazil, Japan and Russia produce more than 167 km^3 of wastewater, which represents half of global municipal wastewater production.

Globally, on average, and according to the data available from AQUASTAT, 60% of the produced municipal wastewater is treated. Nevertheless, this figure needs to be taken with caution. First, actual treatment figures are likely to be lower, as many wastewater treatment plants, particularly in middle and low income countries are functioning below expectation if at all (Oliviera and von Sperling 2008; Murray and Drechsel 2011) which means that actual treatment capacities are below the installed and usually reported capacity. Secondly, data from some low-income countries with large urban populations, such as Nigeria, are not available and therefore not reported in AQUASTAT. And thirdly, while most countries report only secondary and tertiary treated wastewater as "treated wastewater" some countries also include primary treated wastewater, thus making country data aggregation and comparisons difficult. Relatively well documented is the small global tertiary treatment and advanced reuse capacity, which has been estimated for 2014 as about 24 km^3/year globally (GWI 2009). On the other hand and for obvious reasons, treatment capacity is strongly correlated with the countries' income: in lower-middle-income countries on average 28% of the generated wastewater is reported to be treated, and in low-income countries, only 8% is treated, while in high income countries the ratio is closer to 70% (Sato et al 2013).

The cross-city comparison reported by Raschid-Sally and Jayakody (2008) highlighted the contrast between cities in developed and developing countries. In the latter, the capacity for collection and treatment is notably limited, as is the degree of treatment. Figure 2.4 provides a snapshot of the situation which is representative of much of the developing world and flags in particular that collection does not mean treatment. In fact, many sewers end in natural water bodies, not to speak about dysfunctional treatment plants.

2.3.2 Sludge

With wastewater treatment increasing, many countries are solving one problem, but creating a new challenge: managing or disposing sewage sludge. While, thanks to wastewater treatment, cleaner water is discharged to seas, rivers and lakes, large amounts of sewage sludge are produced in the process (Table 2.3) especially in high and middle income countries with high treatment coverage. This sludge has the added drawback that it tends to accumulate heavy metals and other persistent toxic compounds coming from industrial discharges, traffic related pollution and other commercial activities which is limiting its reuse potential.

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