Substance flow analysis of lead and chromium through wastewater management system in a region

M. Gupta, A. Kumar*, S. Kumar, M. K. Jat

Malaviya National Institute of Technology Jaipur, Jaipur-302017, India

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Inappropriate waste management practices have resulted into pollution of the environment in urban and rural areas in India. The pollution from heavy metals requires attention owing to the toxicity of these metals for human beings. The study analyses the management of wastewater in Hanumangarh district, a region in the state of Rajasthan, India and the consequent flow of two heavy metals, lead and chromium. For this purpose, the *status quo* for the management of wastewater has been compared with two alternatives scenarios. The analysis has been performed using the techniques of material flow analysis (MFA). The results indicate the major flows of Pb and Cr in the system and, the points of action for achieving the waste management goals more closely than the current system.

Keywords: Wastewater management; material flow analysis; heavy metals; scenario analysis; urban pollution.

INTRODUCTION

Wastewater management in India has become one of the major problems for Indian cities. The mismanagement of municipal wastewater in Indian cities has led to the accumulation of hazardous substances into the environment [1, 2]. The heavy metals in Indian cities are one of the important classes of hazardous substances in the anthroposphere [3].

Lead and chromium are both heavy metals that have been linked to cancer in humans. Individuals exposed to extremely high levels of lead and chromium suffer from anaemia, weakness, kidney and brain damage. Lead exposure at exceptionally high levels can be lethal. Because lead can pass through the placenta, pregnant women who are exposed to it risk harming their unborn child. Lead is harmful to an infant's nervous system as it develops. Exposure to chromium damages the liver, produces pulmonary congestion and edema, upper abdomen discomfort, nasal irritation, and tooth discoloration [4, 5]. As a result, it becomes important to understand the flow of these substances, i.e., Pb and Cr in a region. The techniques of MFA have been used to study the mass flows of Pb and Cr through a wastewater management system [6]. Scenario analysis has been used to better comprehend the long-term environmental consequences of alternative waste management systems [7].

MFA is based on the conservation of matter and permits the identification and measurement of a substance's sources in system, its temporal accumulation within the system, and its transfer to natural or manmade sinks. Substance-bearing items or materials are transformed, transported, or stored in intermediate stages. Coefficients of transfer are used to characterize the flow of such process inputs to outputs. The MFA methodology is advantageous for identifying the primary sources and sinks of emissions, as well as for planning reduction targets and long-term retention or disposal [8].

The objectives of the study are: (i) to quantify the flow of lead and chromium through a wastewater management system; (ii) to postulate alternative scenarios and quantify the flow of lead and chromium *via* various stages of a wastewater management system in all the scenarios; (iii) to compare the three scenarios in terms of the quantities of wastewater, Pb and Cr being discharged into the environment. The scope of the study is limited to the ULBs of Hanumangarh District in the state of Rajasthan.

MATERIALS AND METHODS

Study Area

The district of Hanumangarh is located at 29° 5' to 30° 6' north and 74° 3' to 75° 3' east. The district covers a total land area of 9,703 square kilometers. Prior to this, the city was known as "BHATNER". In year 1805, emperor Soorat Singh of Bikaner captured BHATNER after defeating Bhatis and as the day of his victory was Tuesday (known as the day of god "Hanuman"), he named BHATNER as "HANUMANGARH". There are total six ULBs in the Hanumangarh district, namely, Bhadra, Nohar, Pilibanga, Rawatsar, Sangaria, and Nagar Parishad Hanumangarh.

* To whom all correspondence should be sent:
E-mail: amitrathi.ucf@gmail.com

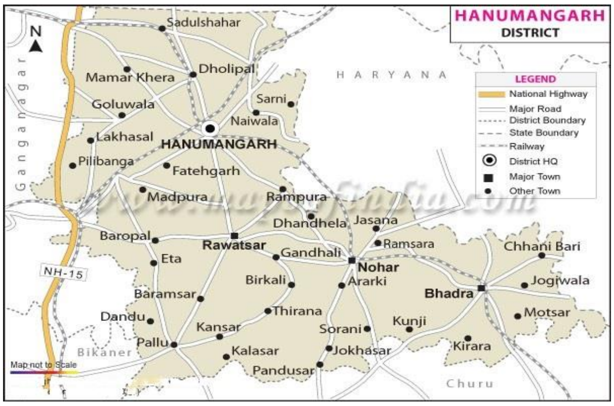

Figure 1. Map of Hanumangarh (Source: [9])

Data Collection

Data have been collected through personal interviews, telephonic conversation with representatives from the various governmental departments in Hanumangarh district. Data were also gathered from the official websites of the city, state and, municipal agencies such as the Department of Industries, CPCB, CPHEEO and RSPCB. An extensive literature search was conducted to determine the lead and chromium concentrations in treated & untreated wastewater, fecal sludge, and sewage sludge.

Scenarios for analysis

The current study looked at three different municipal wastewater management scenarios. The first scenario depicts the current state of wastewater management in Hanumangarh. In scenario 2, the emphasis is on increasing the reach of sewer connections for the households and the wastewater reaching the wastewater treatment plants (WWTPs). The scenario 3 involves increasing wastewater reaching WWTPs and the provision of an engineered landfill for disposal of sewage sludge. Table 1 presents a summary of all the three scenarios.

Scenario 1 illustrates the current state of wastewater management in the area. According to statistics provided by the Hanumangarh administration, the total quantity of wastewater reaching the wastewater treatment facilities for treatment in the is about 2062 million litre (ML)/annum. As all the households in the district are yet to be connected to a sewage system, this wastewater quantity represents a fraction of the volume of wastewater being generated in the district. Majority of the households that are not connected to the sewerage system, are using on-site treatment of wastewater by employing septic tanks. These septic tanks are cleaned every 2-3 years. The fecal sludge from the septic tank is illegally disposed of outside the city limits. The effluent from the septic tank is discharged into the storm water drains and it is assumed that it ultimately makes its way into the agriculture soil.

Table 1. Scenarios for WW management in Hanumangarh urban area

Scenario	WW fraction for treatment	Treated WW Utilization	Disposal of sludge
Present Scenario (Scenario 1)	24% of wastewater reaching the STPs	Application to agriculture fields	Uncontrolled dumping
Enhanced Treatment Scenario (Scenario 2)	90% of wastewater reaching the STPs	Application to agriculture fields	Uncontrolled dumping
Alternate Scenario (Scenario 3)	90% of wastewater reaching the STPs	Application to agriculture fields	Engineered Landfill

Scenario2 is being postulated with the objective of increasing the connectivity of the households to the sewerage system and subsequently the amount of wastewater treated in the district. Fecal sludge (settled sludge) produced by a septic tank is assumed to be disposed off in the forest soil, whereas wastewater treatment plant sludge is discarded in the agricultural soil.

The alternate scenario, referred to as 3, is defined by the incorporation of engineered landfill into the first two scenarios. Production and collection of wastewater are the same as in scenario 2, with the exception that the sludge generated in septic tanks and WWTPs is disposed off in an engineered landfill.

Estimations for MFA

Material flow analysis is being used to examine the wastewater management of the system under consideration. For computational considerations, a one-year timeframe was chosen in accordance with the static MFA method. The following processes are included in the study: collection, sewage system, wastewater treatment plant, septic tank, engineered landfill, and soil (categorized into agriculture soil and other soil).

To calculate uncertainty in the data obtained from literature, the Monte Carlo Simulation (MCS) is employed. The statistical distributions of the input variables are assumed as normal distribution in this study. The confidence interval was selected as 95 percent [10]. The concentrations of lead and chromium in the influent and effluent wastewater, and sludge were taken from literature reviews [11–15] and calculated for this study using Monte Carlo simulation.

The entire quantity of WW generated inside the system boundary is taken into consideration in the first two stages, namely the urban household and the generating process, respectively. The input and output flows for wastewater have been assumed to be the same in all three scenarios.

The total amount of wastewater generated was estimated by taking into account the water supply as specified in [9]. The fraction of grey water in the wastewater generated is taken from [16].

In the sewer system process, the total number of households that are linked to the sewage system is taken into consideration in order to determine the total flow of wastewater. In scenario 1, only a fraction of households is linked to the sewage system (as provided by the Hanumangarh officials), which amounts to 24 percent of the total amount of wastewater flowing through the system. In scenarios 2 & 3, the total amount of wastewater that enters the sewage system is assumed to equal 90 percent of the total.

Septic tank is the method by which black water generated is treated at the household level, and it is taken into consideration in all three scenarios discussed here. In scenarios 1, 2, & 3, the wastewater from all the households without connectivity to sewer network, is discharged into the septic system. The effluent from the septic tank is assumed to go into the other soil.

WWTPs are the facilities that treat wastewater. According to scenario 1, only 24 percent of the entire wastewater is treated; however, according to scenarios 2 & 3, 90 percent of the entire wastewater is assumed to be treated. In all three cases, the flow from the sewage system is received by this mechanism.

Each of the three scenarios involves the use of treated wastewater on agricultural soil. The sludge from wastewater treatment plant is being disposed of in agricultural land and, has been assumed the same in scenarios 1 & 2. The sludge settled in the septic tank is emptied every 2-3 years and is discarded illegally outside the city limits. The sludge from septic tanks has been assumed to be disposed on forest soil in scenario 1 and scenario 2.

Scenario 3 assumes an engineered landfill, and that all of the sludge (from the WWTPs and settled sludge from the septic tanks) is disposed of there. The data regarding the concentrations of lead and chromium in settled sludge and overflow wastewater from septic tank are derived from [17].

The processes, agriculture soil, and forest soil have all been taken into consideration in order to illustrate the movement of pollutants into the soil. Due to the fact that some waste processing products, such as treated wastewater, are used in agriculture soil particularly, the soil has been divided into two categories.

RESULTS AND DISCUSSION

The results from the material flow regarding the overall wastewater quantities, and quantities of lead, and chromium for all the scenarios are discussed in this section.

In scenario 1, the maximum flow is 8,232 ML to agricultural soil, of which only 2,062 ML is treated wastewater, the remaining is untreated wastewater and sludge from WWTPs (Figure 2). In contrast to scenario 1, scenario 2 has more houses connected to the sewer system, resulting in 7429 ML of treated wastewater being discharged in agricultural land (with only 536 ML of untreated wastewater and 74 ML of sludge being discharged) as shown in Figure 3. In scenario 3, the same quantities of treated and untreated wastewater (as in scenario 2) are applied to agricultural soil, however, all of the sludge produced is discarded in the engineered landfill (Figure 4). According to scenario 1, the agricultural soil getting the maximum deposition of Cr is amounting to 4.8 tons (Figure 5). According to scenario 2, the same quantity, i.e. 4.8 tons of Cr are disposed on the agricultural soil, indicating the *status quo* in terms of Cr loadings to the environment. (Figure 6). On the other hand, just 2 tons of Cr are disposed of in the agricultural soil each year, as per scenario 3. Furthermore, by disposing off the 2.7 tons of Cr in the engineered landfill, the harmful effects of Cr may be contained by the landfill (Figure 7).

For the lead fluxes, the highest quantity of lead, i.e. 0.87 tons, is being applied to the agricultural soil in scenario 1 (Figure 8). However, despite the fact that scenario 2 has a larger number of households connected to a sewer system, it discharges higher amounts of lead into the agricultural soil, approximately 1.1 tons per year (Figure 9). The increase in Pb loadings to the agriculture soil is due to change in WW management system in scenario 2 from septic tank to the sewer system and the consequent change in final disposal from forest soil to agriculture soil. In scenario 3, the bulk of the lead is removed from the environment by confining it in an engineered landfill (Figure 10).

Upon examining all the scenarios, it becomes clear that just expanding the treatment system of wastewater will not be sufficient to address the present issue of heavy metal contamination. The bulk of heavy metals still winds up in agricultural soil as shown in scenario 2 (with greater volumes of wastewater being treated in WWTPs).

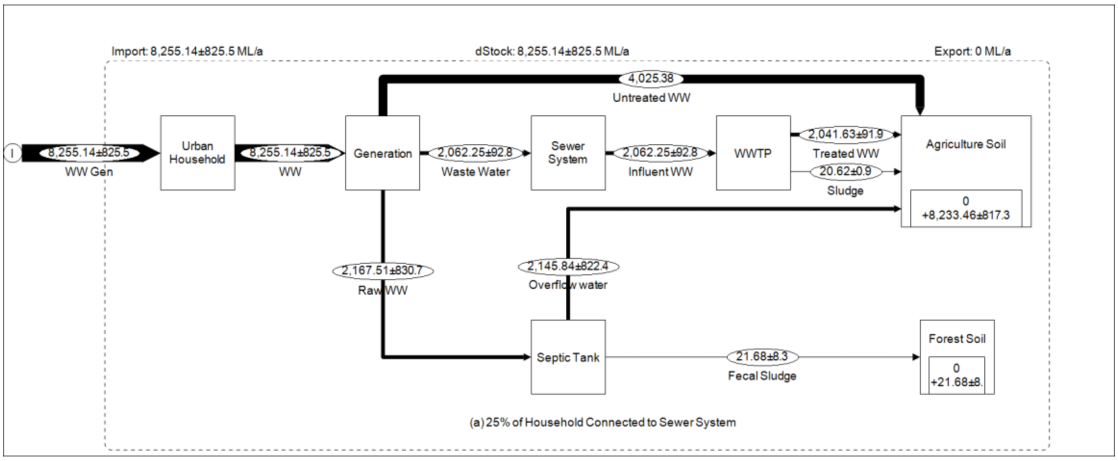

Figure 2. WW flow through Hanumangarh in scenario 1

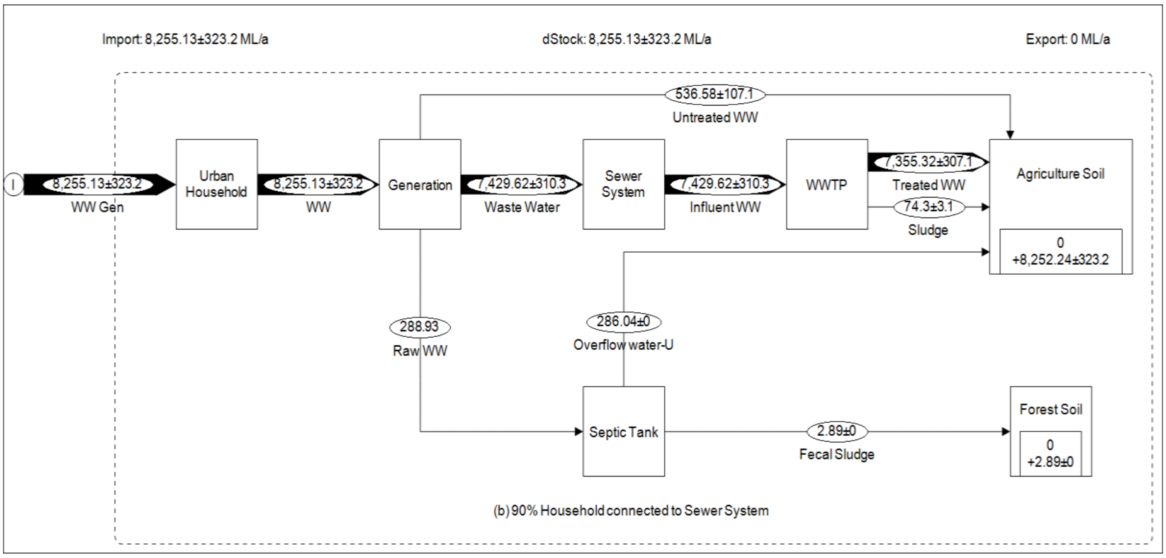

Figure 3. WW flow through Hanumangarh in scenario 2

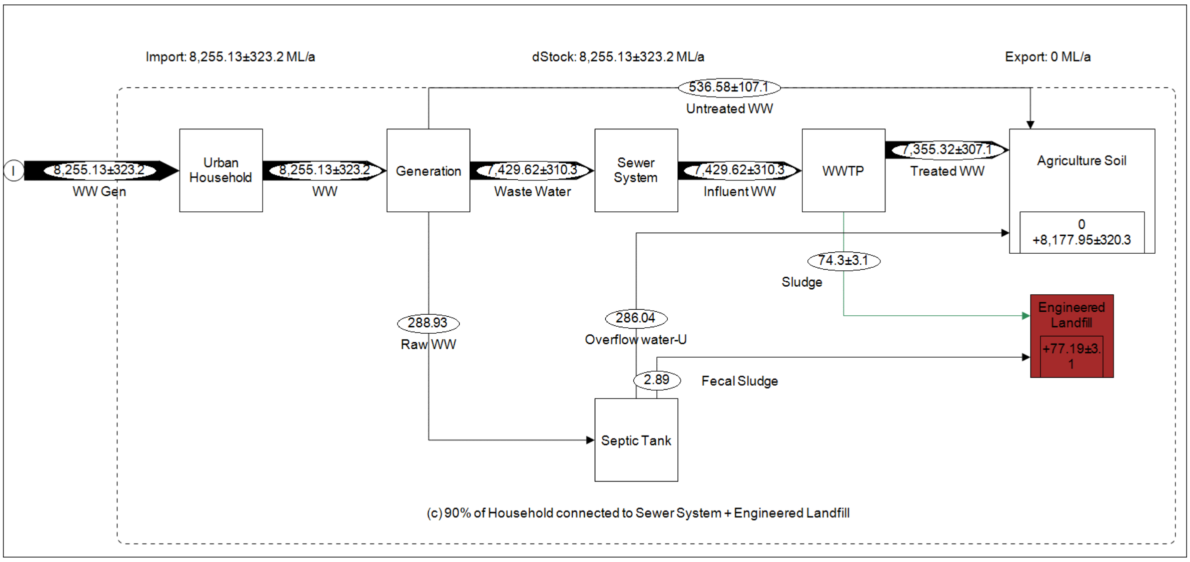

Figure 4. WW flow through Hanumangarh in scenario 3

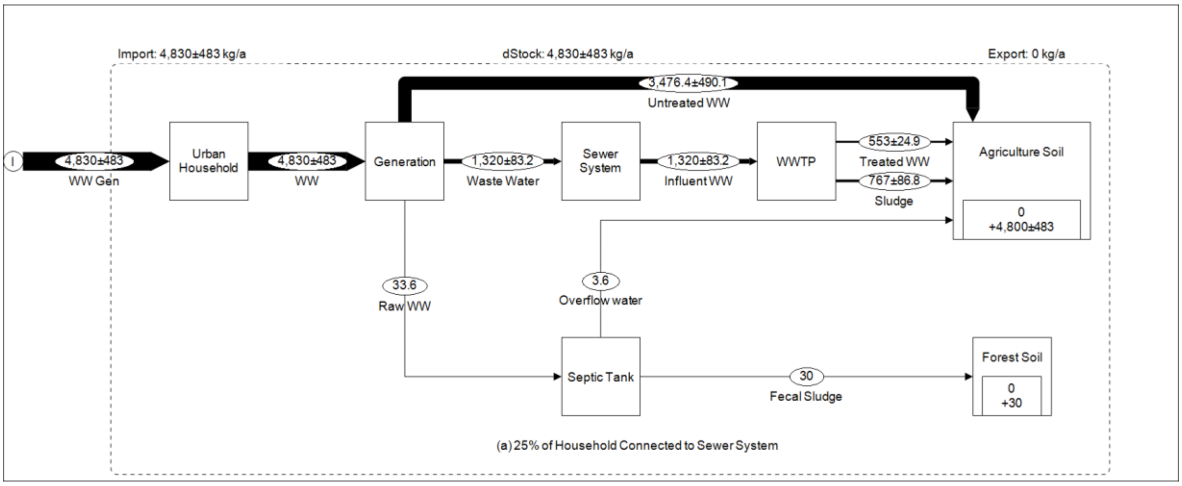

Figure 5. Flow of Cr through WW management system of Hanumangarh in scenario 1

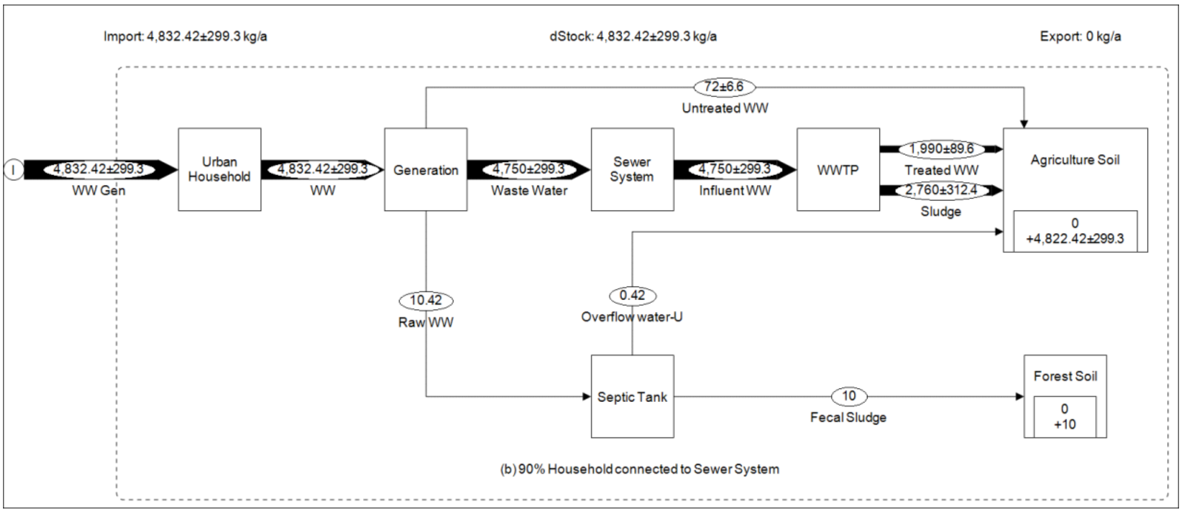

Figure 6. Flow of Cr through WW management system of Hanumangarh in scenario 2

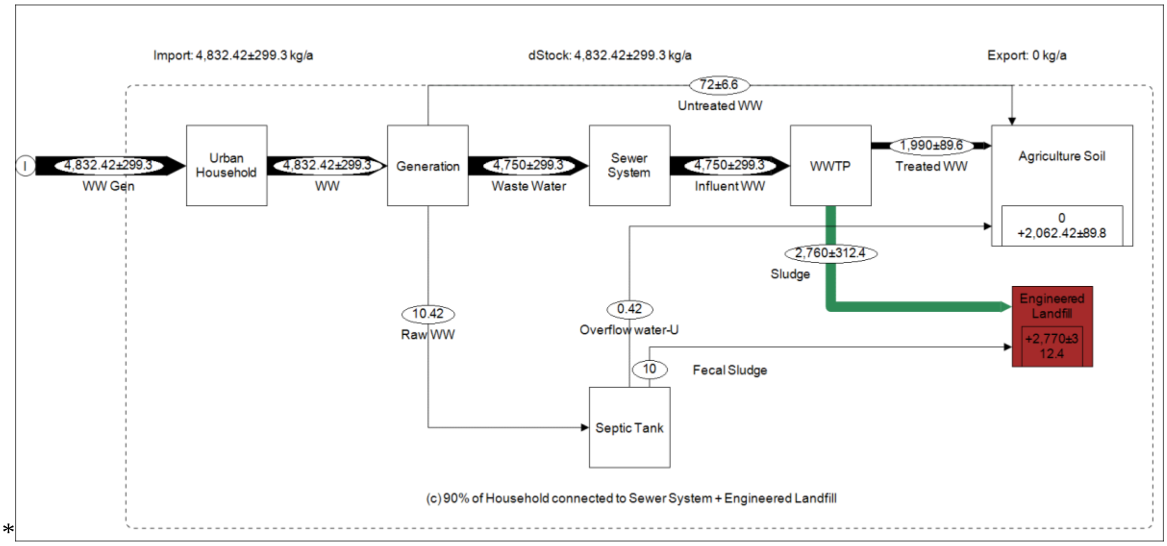

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Figure 7. Flow of Cr through WW management system of Hanumangarh in scenario 3

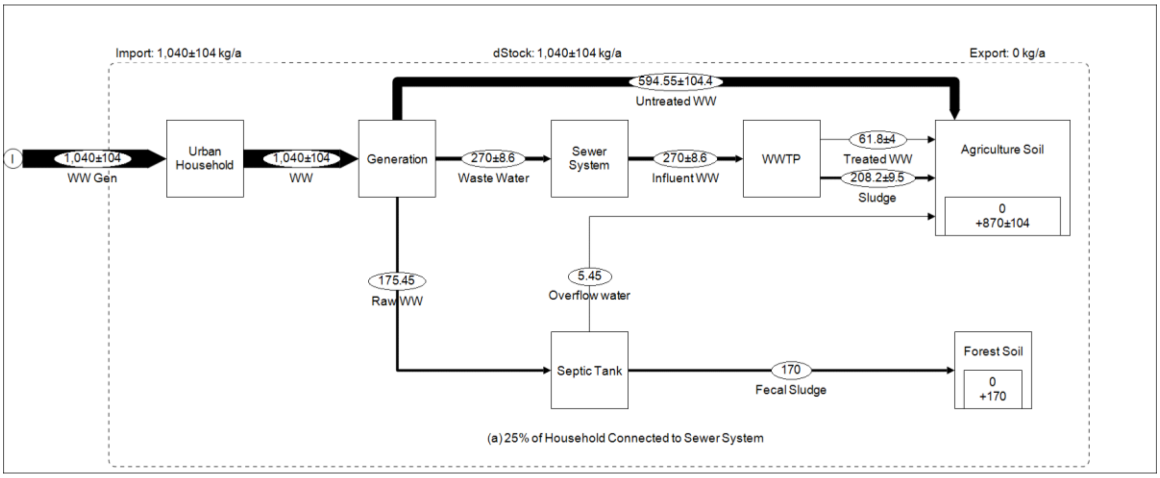

Figure 8. Flow of Pb through WW management system of Hanumangarh in scenario 1

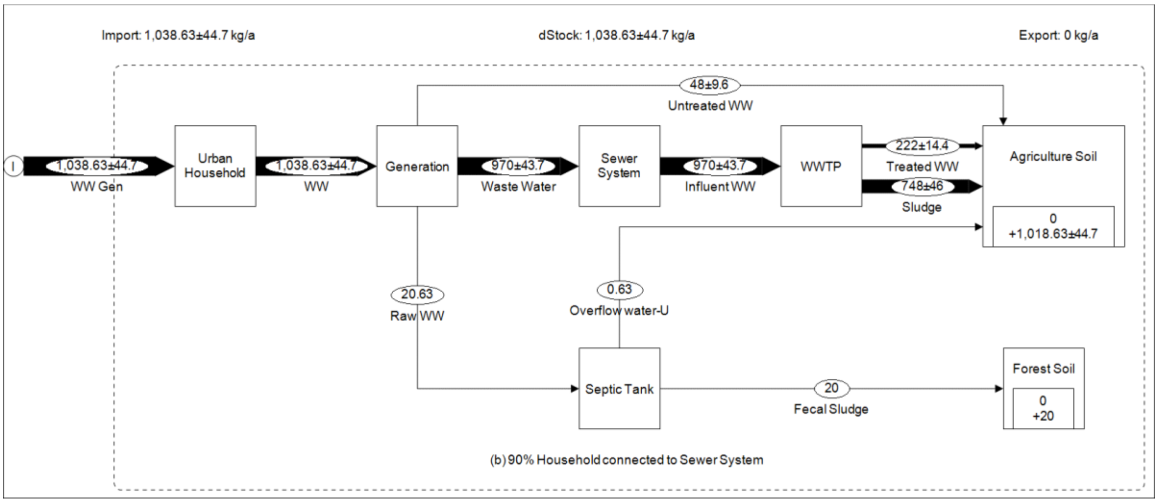

Figure 9. Flow of Pb through WW management system of Hanumangarh in scenario 2

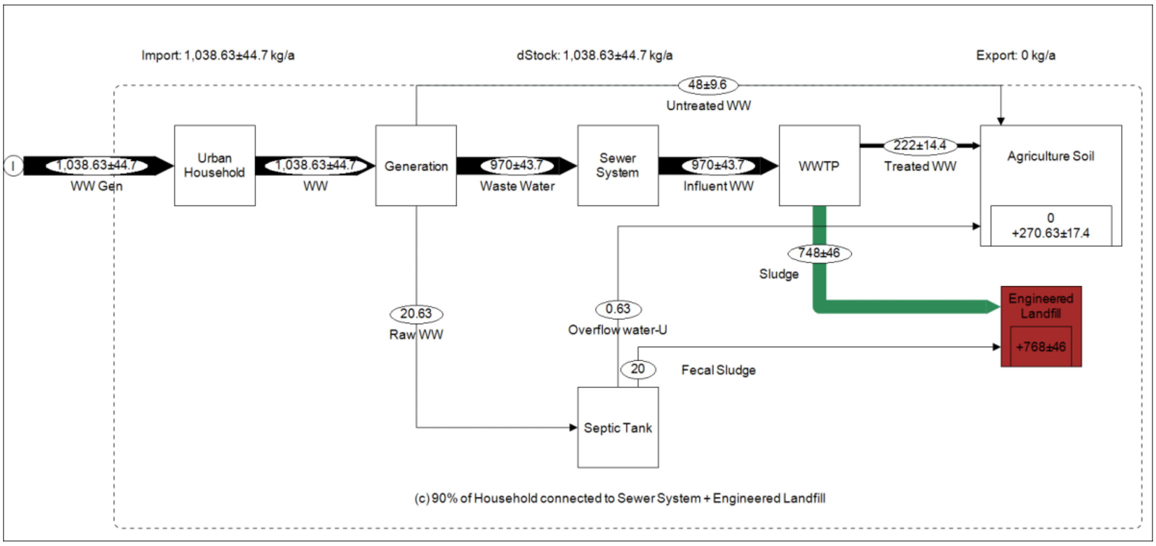

Figure 10. Flow of Pb through WW management system of Hanumangarh in scenario 3

Table 2 compares the amounts of lead and chromium released into the environment from the wastewater management system in Hanumangarh district.

Table 2. The flows of Pb and Cr in three scenarios

	S-1	S-2	S-3
Mass of Pb releasing into the environment (tons/years)	1.04 ±0.104	1.04 ±0.04	0.27 ±0.01
Mass of Cr releasing into the environment (tons/years)	4.830 ±0.483	4.830 ±0.299	2 ±0.09

In scenario 3, on the other hand, the use of an engineered landfill site results in the containment of lead and chromium from the surrounding environment. The present study indicates that the wastewater management system in an urban area can be a significant source of heavy metal pollution in the urban environment. These may enter the wastewater from the materials and activities in an urban area, e.g. runoff from roofs, food, or activities such as car washes [17]. In addition to deposition of pollutants from the atmosphere, application of insecticides and pesticides, as well as recycling of these toxins in the form of compost or sludge, among other also causes soil contamination [18].

Considering that modifying agricultural practices is a time-consuming process, the suggested option for the next several years (10-15) is an engineered landfill with enhanced capacity of the wastewater treatment system, as stated in scenario 3.

As per findings of this study, Hanumangarh emits around 3.46 g of lead per capita per year through wastewater management. For another study [4] in the same region (i.e. the state of Rajasthan) for wastewater management in a smaller system, the per capita use for lead metal comes out through be 6.9 g/capita/year. The results from this are also comparable to the study done at country level in China [19], where the per capita usage was calculated as 2.97 g/year. However, for a study done at city level in China [20], per capita consumption for lead is estimated to be 1.75 kg/year. These differences among the studies may be the result of considering a wide range of sectors in MFA studies for Pb flow [21].

CONCLUSION

Upon examining all the scenarios, it becomes clear that just expanding the collection and treatment of wastewater will not be sufficient to address the present issue of heavy metal contamination in Hanumangarh district. The bulk of heavy metals still winds up in agricultural soil. The material flow analysis shows the importance of engineered landfill and enhanced treatment of wastewater for the better management of wastewater. The use of engineered landfill for the disposal of sludge ensures the isolation of heavy metals from the environment.

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