Impacts of onsite greywater reuse on wastewater systems

Roni Penn, Manfred Schütze, Jens Alex and Eran Friedler

ABSTRACT

Together with significant water savings that onsite greywater reuse (GWR) may provide, it may also affect the performance of urban sewer systems and wastewater treatment plants (WWTPs). In order to examine these effects, an integrated stochastic simulation system for GWR in urban areas was developed. The model includes stochastic generators of domestic wastewater streams and gross solids (GSs), a sewer network model which includes hydrodynamic simulation and a GS transport module, and a dynamic process model of the WWTP. The developed model was applied to a case study site in Israel. For the validation of the sewer simulator, field experiments in a real sewer segment were conducted. The paper presents the integration and implementation of these modules and depicts the results of the effects of various GWR scenarios on GS movement in sewers and on the performance of the WWTP.

Key words | greywater reuse, gross solid transport, sewers, stochastic diurnal patterns, wastewater treatment plants

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INTRODUCTION

Reducing domestic water demands by onsite greywater reuse (GWR) for toilet flushing and garden irrigation has the potential to contribute to alleviation of the stress on natural water resources. GWR affects the quality and quantity of domestic wastewater. Studies on GWR to date hardly gave any attention to the effects of these changes on domestic wastewater quantity and quality, and on urban sewer systems and wastewater treatment plants (WWTPs) performance. Therefore, the research presented in this paper aimed at substantiating conclusions on the extent of the effects that onsite GWR systems, if widely implemented, may have on the urban sewer systems and WWTPs. This will better allow the promotion of GWR schemes, which are expected to result in significant water savings and increase the sustainability of urban water use.

Greywater is generally defined as domestic sewage excluding the streams generated by toilets (blackwater) and in many cases also excluding the streams from kitchens (dark greywater) (Friedler 2004). Onsite GWR for toilet flushing and garden irrigation is thought to be an efficient tool for reducing potable water demand (Campisano & Modica 2010; Penn *et al.* 2012), decreasing the need for exploiting new (and usually costly) water sources, and for enhancing sustainable urban water use. Friedler (2004) has shown that, as the demand for greywater within the urban environment (i.e. for toilet flushing and garden irrigation) is lower than its production, only the less polluted streams from the showers and washbasins (light greywater) come in sufficient quantity to be treated and reused.

With an increase of GWR, wastewater discharges from the houses decrease, with the main reduction occurring during the morning and evening peaks (Penn *et al.* 2012, and others). In upstream links of the sewer system, where flows are low, the decrease in flow reduces gross solid (GS) movement and deposition may occur. Further downstream, where flows are higher, their movement improves (e.g. Penn *et al.* 2014; Mattsson *et al.* 2015; Penn 2015; Spence *et al.* 2015). However, sediment accumulation and possible resulting blockages in upstream links of the sewer systems are not necessarily an outcome of these effects. Flows in the sewer, especially in the upper parts, are unsteady and non-uniform. A momentary high flow might be sufficient to move stationary solids out of the sewer stretch, and hence may prevent blockages. The effect of these higher pulses of flows on GS movement requires further examination, and is presented in this paper. GWR also affects

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the wastewater composition. With high reductions in flow and a smaller reduction in pollutant loads (as a result of the needed treatment before its reuse), pollutant concentrations in the wastewater do increase (Penn *et al.* 2012). This may well affect the performance of the WWTP, an effect which also is further examined and presented in this work.

As a means to examine the effects of GWR on sewer systems and WWTPs, an integrated stochastic simulation system for GWR in urban areas was developed and implemented for a real network (separate sewer system) and WWTP in Israel. An up-to-date user-friendly simulation system, SIMBA# (Alex *et al.* 2013; Ogurek *et al.* 2015), served as a platform. The simulation model starts at the single house scale, goes through the sewer network and ends at the WWTP outflow. It includes stochastic generators of domestic wastewater streams and GS, a municipal sewer network model which includes full hydrodynamic flow simulations, a GS transport module, and simulation of biochemical processes occurring within the WWTP. Setup and implementation of the stochastic generator and the GS transport simulator were previously developed and described by Schütze *et al.* (2014) and Penn (2015). The next sections of the present paper provide a short introduction to each of these modules. A short description of the previously developed modules, and a broader description of their integration with the WWTP and of the implementation of the integrated model for the examination of the effects of GWR on a represented sewer system and WWTP, will be presented in more detail subsequently.

Stochastic generation of domestic wastewater streams

Most of the characterizations and generators for domestic wastewater streams and GS production found in the literature (e.g. Butler *et al.* 1995; Friedler & Butler 1996; Friedler *et al.* 1996; Langergraber *et al.* 2008; Gato-Trinidad *et al.* 2011; Rodríguez *et al.* 2013) are deterministic or deterministic models converted to stochastic ones by adding a stochastic component. These do not take into account all the many dependencies among wastewater generation events and quantities within a household. These dependencies are not rigid but elastic and can change with time, person, appliance, etc. As a result, domestic wastewater streams are subject to high variability and fluctuation (Friedler *et al.* 1996; Shteynberg 2015; Spence *et al.* 2015, and others). Characterization by averaging, as suggested in some of these models, attenuates the peaks of the momentary upstream flows, which may significantly affect simulation results of modelling GS movement. Further, most of these existing models do not provide a description of outflows from individual houses; thus they do not represent the behaviour in the upper parts of the sewer system, in which the variability is more pronounced (e.g. Blanksby 2006; Butler & Davies 2010) and where higher risk for blockages occurs. Moreover, most of the above-mentioned characterizations and generators do not differentiate between all of the individual domestic wastewater streams, which, however, is needed for a GWR analysis. Blokker *et al.* (2010) developed a detailed stochastic prediction of water demand patterns from different household appliances, taking into consideration many parameters and their dependencies. However, these require a large amount of statistical information, making it difficult to implement the model for an alternative case study. For this paper, a detailed stochastic generator for individual domestic wastewater streams and GS production, as developed by Penn *et al.* (2017) in an easy-to-use tool was used.

Description of GS transport in sewers

There has been some earlier work on GS characteristics and transport in sewer systems (Babaeyan-Koopaei *et al.* 1999; Schütze *et al.* 2000; Digman *et al.* 2002; Butler *et al.* 2003, 2005; Walski *et al.* 2011, and others). For example Schütze *et al.* (2000) have confirmed by a regression analysis the results of the detailed model by Babaeyan-Koopaei *et al.* (1999), establishing that a solid would move if and only if both water velocity and water level exceed a certain threshold. A linear relationship, with two calibration parameters, was found between the GS velocity and the wastewater velocity. Walski *et al.* (2011) also stated that a minimum flow Q should be exceeded in order for a GS to be moved. Gouda *et al.* (2001) modelled GS transport in a stochastic way, using Markov chains. However, none of these modelling approaches seem to have found their way in commonly applied simulation programs, nor have any easy-to-use simulators for GS transport been reported. The subsequent sections describe the implementation of a GS simulator in an easy-to-use simulation framework.

Inflows to WWTP

For planning and simulation of conventional WWTPs, diurnal patterns of flow and concentrations prove very useful. Successful procedures have been developed for their description by analytical functions, which are useful in particular when measurement data are not available or not sufficient. For example, Langergraber *et al.* (2008) defined diurnal variations of flow and pollutants in domestic wastewaters by means of a Fourier series with easily determinable coefficients. Several authors derived stochastic extensions of this concept (e.g. Rodríguez *et al.* 2013), which, however, fall short of the principle of simplicity. In the present work, the wastewater generation is modelled using the stochastic procedure outlined in subsequent paragraphs.

METHODS

Simulation system

The simulation system that served as a platform for the research was SIMBA#, an integrated simulator for sewer systems, WWTPs and river water quality (Alex *et al.* 2013; Ogurek *et al.* 2015). The hydrodynamic modelling modules of SIMBA#, which are based on an extended version of the USEPA SWMM (Storm Water Management Model) (Rossman 2004, USEPA website) were applied for simulating wastewater flows. These yield the full dynamic solution of the Saint Venant differential equations. The stochastic wastewater and GS generator served input data to the hydrodynamic simulations of the flows and to the GS transport simulator which was developed as an add-on module in SIMBA# (Schütze *et al.* 2014). The quantity and quality of the wastewater flow and the GSs at the outlet of the sewer system served as input to the WWTP model.

Case study

The effects of GWR on wastewater systems were studied by modelling a representative, separate, urban sewer system of a densely populated neighbourhood located in Netanya, a coastal city in Israel. The neighbourhood has an area of $\sim$1.3 km^2, accommodating some 15,000 residents living in multiple-flats buildings. The sewer system is composed of 154 nodes and 153 links, with diameters ranging from 0.2 m (upstream links) to 0.4 m (downstream ones) and an overall length of about 6 km. Figure 1 presents the layout of the modelled sewer network. Further information on the case study site can be found in Penn *et al.* (2013).

For examination of the effects on the WWTP, a dynamic model of Netanyas WWTP has been set up, based on the Activated Sludge Model No. 3 (Figure 2). Based on information obtained from Netanya Water Ltd, the plant has an average dry weather flow rate of 39,000 m^3/d. Although the real plant has an equalization tank at its inlet, which also has been included in the model, it is not being used for the simulation of the various scenarios, since most of the time it is not in use.

Overall, the WWTP consists of the following four process steps:

- Mechanical pre-treatment (primary clarifier, equalization tank).

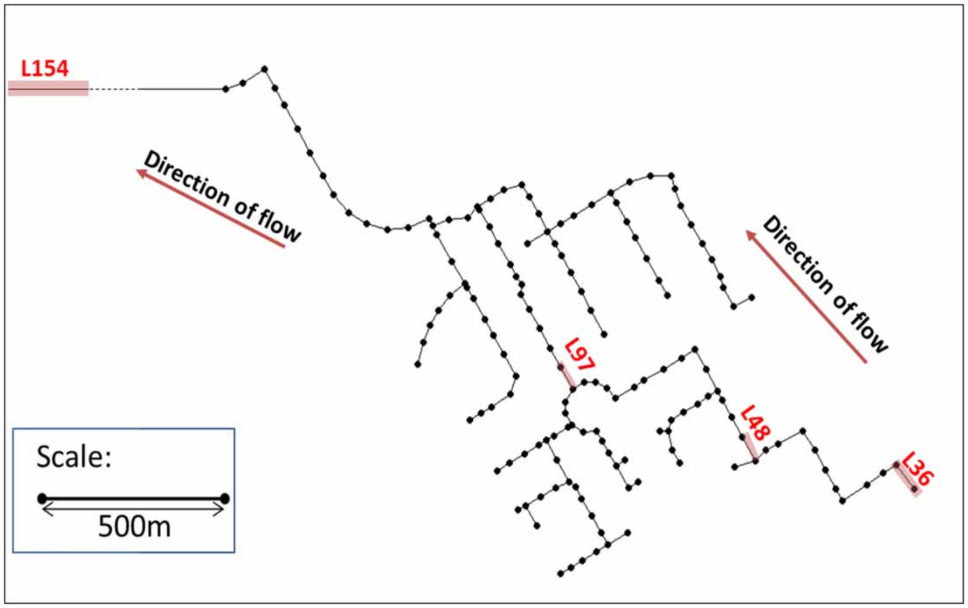

Figure 1 | Layout of the represented sewer system. Links referred to in the 'Results and discussion' section are marked in the figure. L154 is a long trunk sewer located further downstream, and due to lack of space a dotted line is separating it from the main part of the sewer system.

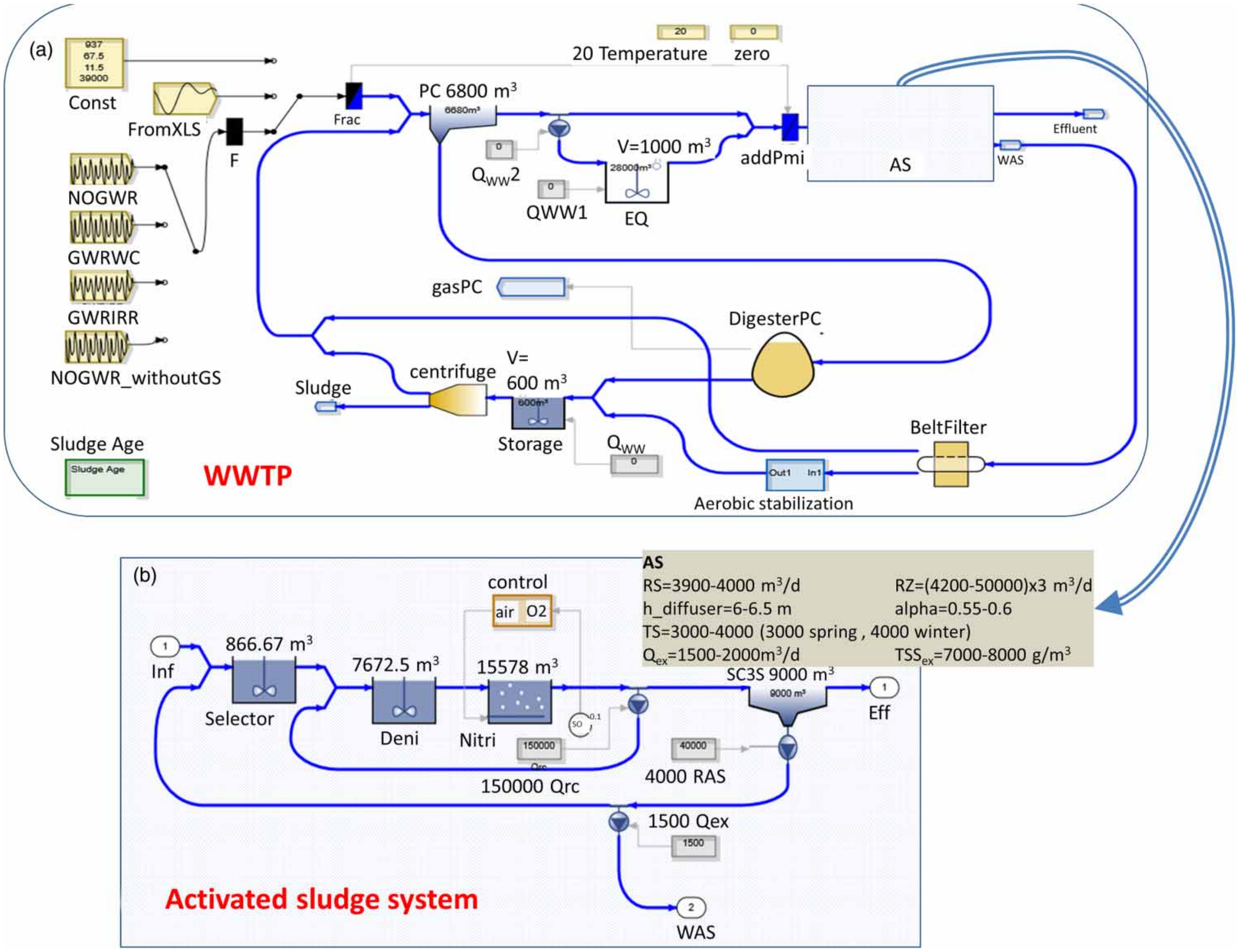

Figure 2 | Model of Netanya WWTP: (a) the entire plant, including sludge treatment line, (b) subsystem 'activated sludge system'.

- Biological wastewater treatment with typical plant layout (pre-denitrification).
- Anaerobic digestion of primary sludge.
- Aerobic stabilization of excess sludge (this represents a specific feature of Netanya WWTP. Thickened sludge is, after hydrolysis, further processed in a cascade of anaerobic tank, denitrification and nitrification. By adding air, the sludge gets further stabilized.

Stochastic generator of domestic wastewater streams module

Stochastic generation of GS and individual wastewater streams from household appliances served as input to the hydrodynamic simulation of the flows and to the GS transport simulator. The generator was developed while considering the many dependencies between water-use events in a household, and the varying elasticity of these dependencies, both making the characterizing of these discharges by 'classic' stochastic distributions almost impossible. Data for the stochastic generator were derived from an end-use water-usage measurement campaign (and the resultant wastewater generation) (Shteynberg 2015). Generation of these streams was carried out by sampling with replacement from the observed data: in our context, sampling daily diurnal wastewater discharge patterns from domestic appliances (kitchen sink, showers, washbasin, bathtub, dishwasher, washing machine and toilet) of different households, while keeping the observed domestic and neighbourhood structures. The generated patterns were validated with flow measurements of a real sewer system located near the case study under consideration. Both areas are characterized by similar socio-economic characteristic and household size distribution (Penn *et al.* 2017). Diurnal patterns for 7 days of simulation were generated for non-GWR households. Diurnal patterns for GWR households were derived from these patterns.

Further details on the measurement campaign can be found in Shteynberg (2015) and on the stochastic generator and its validation in Penn *et al.* (2017).

GS transport simulator module

The GS transport module employed here takes a microscopic approach, i.e. it tracks the movement of each individual GS along its way through the sewer system.

The GS module received hydraulic information on the wastewater flow, velocity and water depth calculated by the hydrodynamic calculations for each element of the sewer system. It was assumed that the GSs do not affect the in-sewer flow. GS velocity was determined according to its relationship with the wastewater velocity, as derived by Penn (2015) (Equation (1)).

$$V_{GS} = 17.949 \times V_{WW}^{0.747} \tag{1}$$

where V_{GS} and V_{WW} are the GS and wastewater velocities, respectively (m/d).

For the validation of the model, field experiments in a real sewer segment were conducted, where GS movement was traced by using RFID (radio frequency identification) and light sticks (tracked by a web-cam placed in a downstream manhole) combined with flow characteristics in the sewer segment (discharge, velocity and depth of flow). High compatibility between the simulation results and the actual measurements was obtained, showing a linear correlation with a high R^2 value of 0.85 (further description can be found in Penn (2015)).

Figure 3 shows the setup of the model integrating the stochastic GS and wastewater generator, the SWMM block within SIMBA# (hydrodynamic simulation) and the

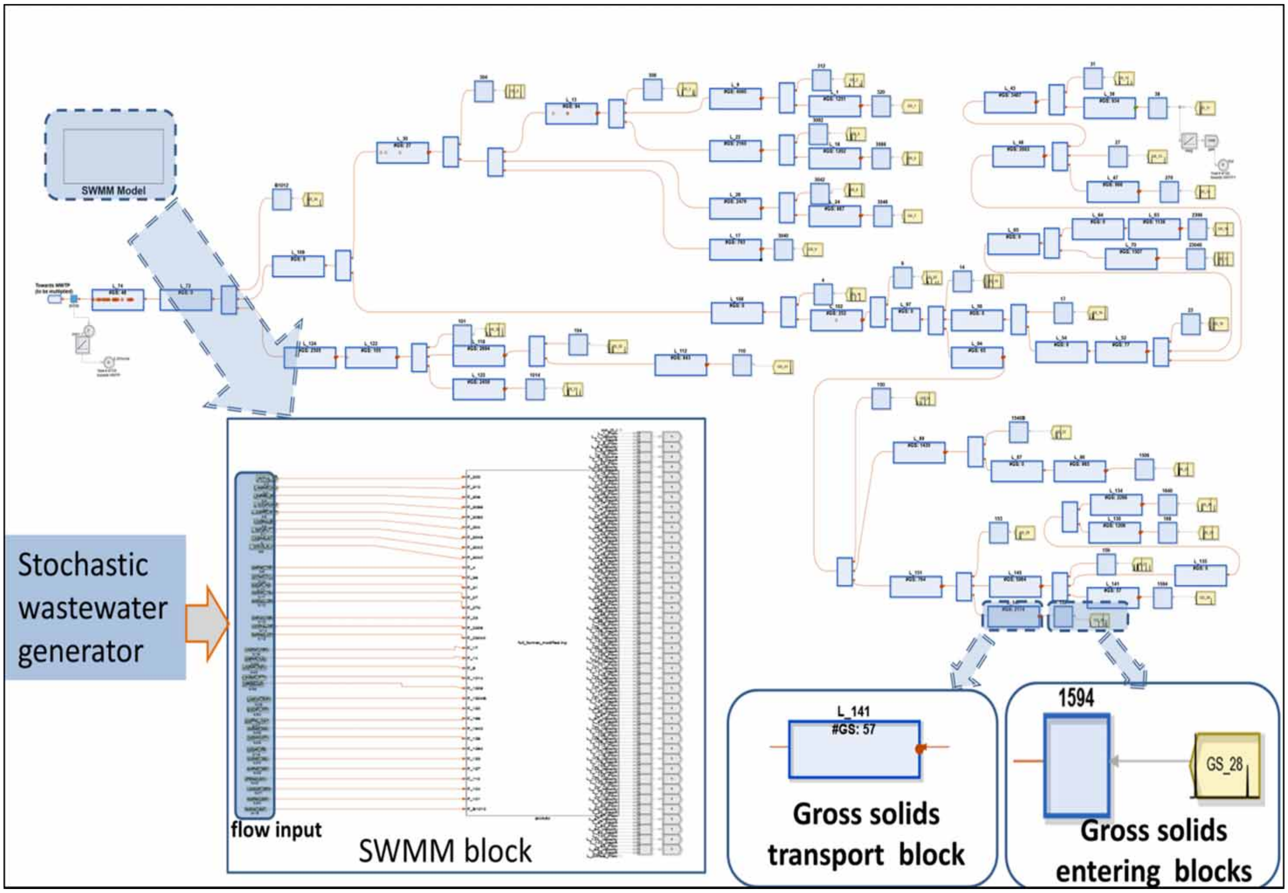

Figure 3 | Representation of the integrated model within SIMBA# including the wastewater and GS stochastic generator, hydrodynamic simulation of flows and GS transport module. Enlargement of figure components for better description: the dashed arrows indicate enlargement description of the components marked with a dashed square.

GS transport module for the case study under consideration. Wastewater and GS production are calculated by the generator for the given population size, and then fed into the Simba#-SWMM block and transport module, respectively, by means of interface files.

For simplification of the modelling process, households in the modelled sewer network were grouped into 34 clusters, each discharging its wastewater and GSs to a different junction in the sewer system. Within the GS transport module, sewer segments were further aggregated to one pipe between each of these discharge junctions. A change in diameter or extreme change in slope disassembled the aggregated pipes into smaller aggregated sections (each having the same diameter and similar slope).

WWTP module

For the influent to the WWTP, GS and appliance discharge loads are merged. For the pollutant loads of the discharges from each household appliance, values as cited by Penn *et al.* (2012), these being based on Friedler *et al.* (1996), Almeida *et al.* (1999) and Friedler (2004), are used. For converting each individual GS to its chemical content the following pollutant loads contained in faecal GS (g/(cap·d)) have been used: chemical oxygen demand (COD) 31, N 1.5, P 0.6 and mass of 123 (Lange & Otterpohl 2000; Friedler *et al.* 2013).

The sewer system under consideration (as described above) represents just a small part of the system feeding into Netanya WWTP, with a dry weather flow of 1,364 m^3/d, as compared with 39,000 m^3/d arriving at the WWTP. In order to avoid having to model all of Netanya's sewer system, the outflow derived from the sewer system simulations was multiplied by a corresponding factor and attenuated by means of a Nash cascade (to allow for the consideration of flow attenuation within the system over a distance of about 10 km) and up, scaled in order to emulate the superposition with the inflows of the other subcatchments of the Netanya drainage system.

Output from the sewer system, greywater and GS simulation modules was then fed as influent to the WWTP model and allowed analysis of impacts of GWR on wastewater treatment For the activated sludge system, default parameters for domestic wastewater were used (Alex *et al.* 2015). The model performance was observed to be comparable to the real plant.

Scenarios simulated

Three types of wastewater streams of GWR houses were considered:

- Type 1 (No GWR) – no GWR is practised and the combined domestic wastewater streams (incorporating discharges from all domestic sources) are discharged into the sewage system.
- Type 2 (GWR WC) – greywater generated from the bath, shower and wash basin (i.e. light greywater) is treated and used for toilet flushing. Excess light GW that is not used for toilet flushing is discharged to the sewage system as overflow, prior to treatment (as raw greywater).
- Type 3 (GWR WC IRR) – the same as type 2, but the excess greywater flow (after treatment) is used for irrigation.

The treatment applied in houses of type 2 and 3 was biological treatment by an RBC (rotating biological contactor) based system. Quality of treated GW was taken from data obtained from an experimental pilot-scale RBC based unit, situated at a married couples' dormitory in the Technion – Israel Institute of Technology, which was operated for more than 3 years (Friedler *et al.* 2005; Aizenchtadt *et al.* 2009). These were considered as the baseline quality characteristics for toilet flushing and for toilet flushing and garden irrigation in the second and third scenarios, respectively.

Average and 10th and 90th percentiles of the daily wastewater discharge per person per household size, for each scenario, are presented in Figure 4. Further description of the quantity and quality of these streams and their generation can be found in Shteynberg (2015) and Penn *et al.* (2012, 2017).

Three GWR scenarios were modelled, simulated and analysed. In each scenario, all houses implemented the same type of GWR: scenario (1), the current situation in Israel, where none of the houses reuse greywater; scenarios (2) and (3), extreme implementation of GWR where all houses implement type 2 or 3 GWR (as described above), respectively. These scenarios are not likely to fully occur, but as they result in the highest water saving they can potentially be the most problematic when the movement of GSs is concerned.

RESULTS AND DISCUSSION

Simulation results suggest that, with the increase in GWR, the momentary flows are reduced; thus reducing velocities and water depths (e.g. Penn *et al.* 2013) affect the movement of GSs.

The effects of high flows on GS transport are shown in Figure 5 where histograms of the GS travel time through

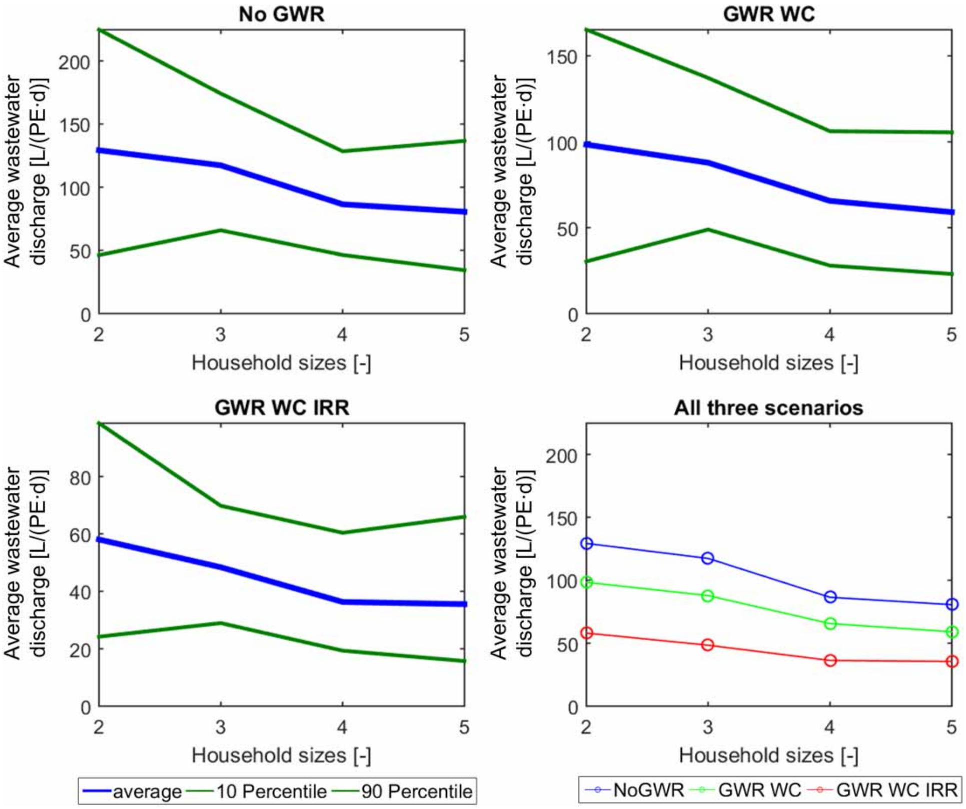

Figure 4 | Average daily wastewater discharged from one person per household size; (a)–(c) averages and 10th and 90th percentiles for the three types of houses considered, respectively; (d) averages of all the scenarios simulated.

the sewer system are presented. A GS travel time is defined as the time it takes it to reach the outlet of the sewer system from the point of its entry into the sewer system. This time includes the GS's movement and stationary time. One can see that, in all scenarios, most of the GSs have short travel time; i.e. if a GS is 'caught' by a high flow, it is transported mostly continuously through the entire sewer system. However, if a GS enters the sewer system when flows are low, it needs to 'wait' for flow velocities and water depth to exceed their threshold values in order to start moving. It further can be observed that in links located downstream (e.g. Link 154) the higher percentage of GSs are found in the range of shorter travel time than that of upstream links since their total travel distance is shorter. This phenomenon was observed in other links of the sewer system as well. As flows are reduced (with GWR), the travel time of the GSs increases and higher percentages of GSs can be found in the longer travel time intervals. In the upstream Link 36, in the scenario with GWR for toilet flushing and garden irrigation, all GSs do have a travel time of zero since they all do not leave this stretch. In some downstream links, due to their higher slopes although velocities were high, water depths were not sufficient to move the stationary GSs (results not shown). The stationary GSs decrease the organic load of the influent of the WWTP. This effect is broadly explained in the next paragraph.

Simulation results for the No GWR scenario suggest that the WWTP can buffer the peak loads caused by incoming bulks of GS fairly well. For the No GWR scenario, the total suspended solids concentration reaches a typical equilibrium value of around 3,000 mg/l (Figure 6(a)), while NH_4 concentrations in the effluent reach around 1 mg/l and NO_3 around 10 mg/l (Figure 6(b)). For the scenarios GWR WC and GWR WC IRR, it should be noted that, due to some GSs getting 'stuck' in the sewer network due to low flows, incoming loads to the WWTP are less than in the No GWR scenario. Furthermore, the composition of the wastewater arriving at the WWTP changes (different COD:N ratio), having negative impacts on the treatment efficiency of the WWTP.

Analysis of the simulation results of the WWTP for the GWR scenarios (GWR WC, GWR WC IRR) indicates that

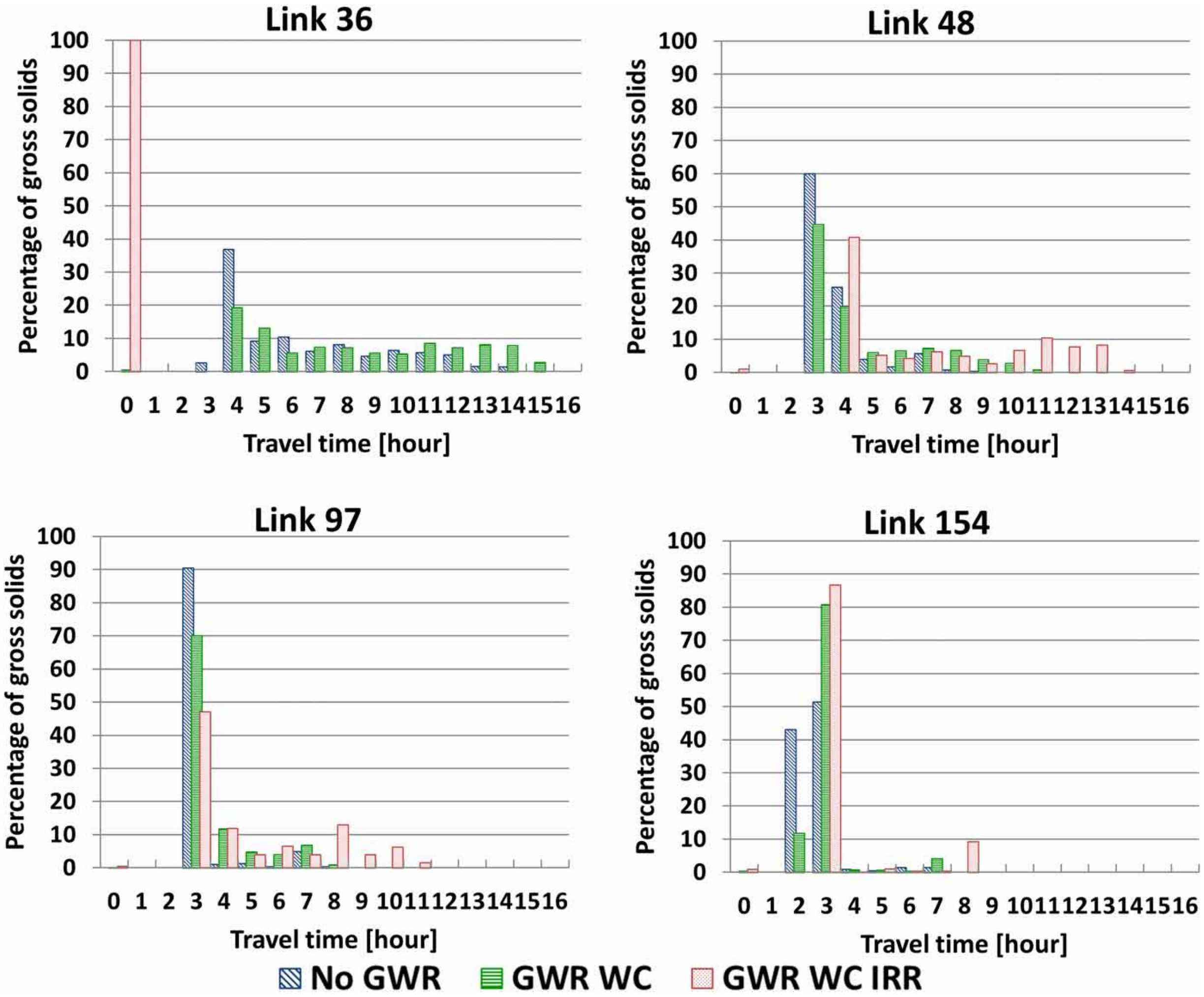

Figure 5 | Histograms of the GS travel time from their point of input to the output of the sewer system under consideration. The position of the links in the figure correspond to their location in the sewer system from the most upstream link on the top left (link 36) and the most downstream link on the bottom right (link 154).

great care has to be taken with regard to nitrogen when applying GWR. Without additional measures, WWTP effluent tended to have too high nitrate concentrations. This can be attributed to unsatisfactory COD:N ratio in the WWTP influent: stationary GSs which accumulate in the sewer system and GW treatment before reuse remove part of COD, but not of N. Therefore, the influent COD loads do not correspond anymore to the incoming N loads (see also Table 1).

Therefore, additional measures are to be taken. These could include:

- addition of carbon source;
- application of processes for improved N treatment (e.g. anaerobic ammonium oxidation (Anammox));
- urine separation (to take out part of the N from the greywater).

CONCLUSIONS

As a means for the examination of the effects of various GWR scenarios on sewer systems and WWTPs, an integrated stochastic simulation system was developed and validated. Simulation of the model on a real case study showed that in extreme situations, as in upstream links of the sewer system, where flows are low, with high implementation of GWR, GSs may accumulate in the sewer pipes, and the risk of blockages may increase. With up to 40% savings

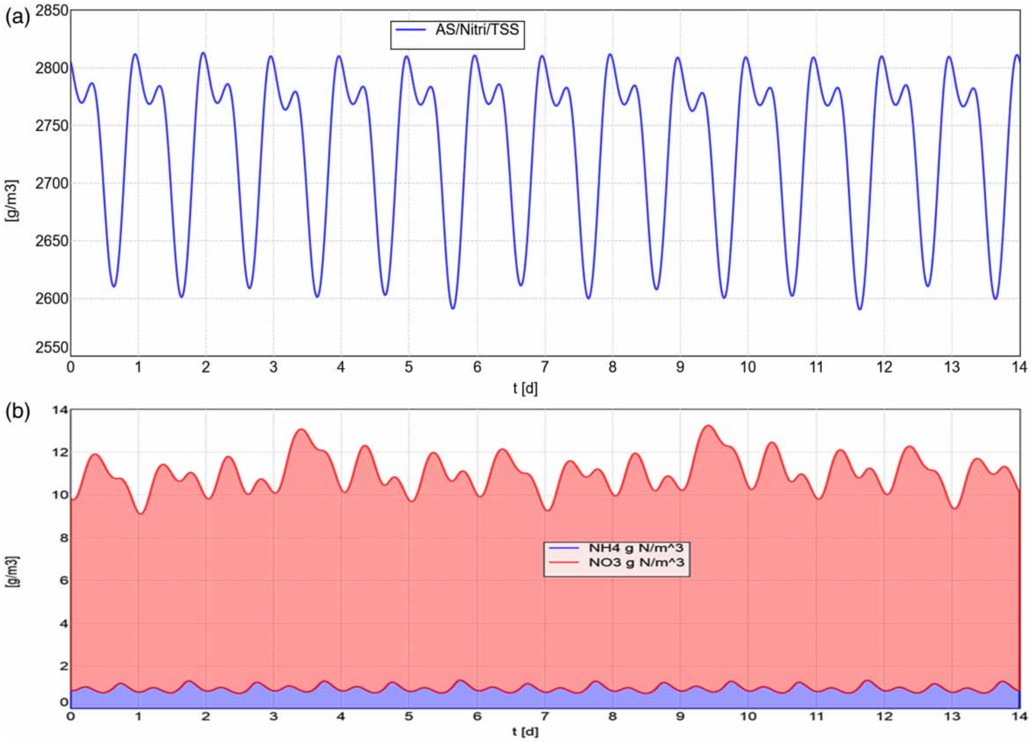

Figure 6 | Simulated WWTP performance: (a) total suspended solids in the activated sludge reactor; (b) NH_4 and NO_3 (stacked) – No GWR scenario.

Table 1 | Influent loads under various GW treatment scenarios

Inflow to WWTP (incl. GS) in 7 days	COD (kg)	TKN (kg)	P (kg)
No GWR	7,698	1,355	595
GWR WC	6,225	1,315	564
GWR WC IRR	3,203	1,233	514

COD: chemical oxygen demand; TKN: total Kjeldahl nitrogen.

in water consumption, when greywater is being reused for toilet flushing and garden irrigation, we strongly promote its implementation, especially in households not located in the most upstream links of the sewer systems. For households located in the most upstream links, milder forms of reuse should be considered (e.g. reuse only for toilet flushing); alternatively these sewer pipes can be constructed with smaller diameters, and enlargement of existing systems can be postponed.

Analysis of the simulation results of the WWTP for the GWR scenarios (GWR WC, GWR WC IRR) indicates that a WWTP might face challenges regarding the nitrification–denitrification processes; hence, too high nitrate concentrations in the WWTP effluent may occur. Therefore, additional measures such as addition of carbon source, application of processes for improved N treatment (e.g. Anammox) and urine separation (to take out part of the N from the greywater) appear to be advisable.

Subsequent research steps may include the examination of the effects of reduced flows on the transport of additional types of solids and the effect of disintegrating/dissolving solids (large solids being divided to smaller solids and later possibly being disintegrated/dissolved completely), increasing the concentrations of the liquid phase of the wastewater stream and, finally, impacting the influent concentrations of the WWTP. The movement of accumulated and aggregated solids may be different from the movement of the individual, the original, solids (as suggested for example by Littlewood & Butler (2003)). Furthermore, these larger solids are expected to affect sewer flow. Moreover, integrating stochasticity to the models describing the solids movement may constitute subject for further research.

An outcome of this research is a stochastic, quantitative and qualitative complex modelling of the entire sewer system under evolving future alternatives for reduction in water consumption. Currently this information is limited in the scientific and engineering literature. The integrated model can potentially serve as a tool for analysing any new sewer system or existing sewer systems subject to changes in flows, as with the result of GWR just as presented in this work or other water saving measures. The model can be simulated for predicting 'hot spots' for GS accumulation and consequently can serve as means to support prevention of blockages in these systems. The intelligent, and relatively easy to implement, method to stochastically characterize diurnal patterns of domestic wastewater streams can be adapted to additional case studies and data sets. Further, if done by intelligent considerations, the model can also be adopted in the broader scope of many other research projects related to sewer systems such as optimization of sewer system performances, rehabilitation of sewers, fate of pollutants in the surrounding environments (e.g. water sources), etc.

The research results are further expected to increase water systems efficiency and sustainability by assisting in long term planning of introducing water saving measures to the urban sector and in designing and managing the urban wastewater systems that are influenced by these systems.

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REFERENCES

Aizenchtadt, E., Ingman, D. & Friedler, E. 2009 Analysis of the long-term performance of an on-site greywater treatment plant using novel statistical approaches. *Urban Water Journal* **6** (5), 341–354.

Alex, J., Ogurek, M. & Schütze, M. 2013 A novel simulation platform to test WWTP control options. In: *11th IWA Conference on Instrumentation, Control & Automation (ICA), Narbonne*.

Alex, J., Dürrenmatt, D. J., Langergraber, G., Hobus, I. & Spering, V. 2015 Voraussetzungen für eine dynamische Simulation als Bestandteil einer Kläranlagenbemessung nach DWA-A 131. *KA – Korrespondenz Abwasser, Abfall* **62** (5), 436–446.

Almeida, M., Butler, D. & Friedler, E. 1999 At-source domestic wastewater quality. *Urban Water* **1**, 49–55.

Babaeyan-Koopaei, K., Butler, D. & Davies, J. 1999 Modelling of GS transport in sewers. In: *8th International Conference on Urban Storm Drainage*, *Sydney*.

Blanksby, J. 2006 Water conservation and sewerage systems. In: *Water Demand Management* (D. Butler & F. Memon, eds). IWA Publishing, London, pp. 107–128.

Blokker, E. J. M., Vreeburg, J. H. G. & van Dijk, J. C. 2010 Simulating residential water demand with a stochastic end-use model. *Journal of Water Resources Planning and Management* **136** (1), 19–26.

Butler, D. & Davies, J. W. 2010 *Urban Drainage*, 3rd edn. T & F Books, UK.

Butler, D., Friedler, E. & Gatt, K. 1995 Characterising the quantity & quality of domestic wastewater inflows. *Water Science and Technology* **31** (7), 13–24.

Butler, D., Davies, J. W., Jefferies, C. & Schütze, M. 2003 Gross solid transport in sewers. *Proceedings of the Institution of Civil Engineers: Water and Maritime Engineering* **156** (2), 175–183.

Butler, D., Littlewood, K. & Orman, N. 2005 A model for the movement of large solids in small sewers. *Water Science and Technology* **52** (5), 69–76.

Campisano, A. & Modica, C. 2010 Experimental investigation on water saving by the reuse of washbasin greywater for toilet flushing. *Urban Water Journal* **7** (1), 17–24.

Digman, C. J., Littlewood, K., Butler, D., Spence, K., Balmforth, D. J., Davies, J. & Schuetze, M. 2002 A model to predict the temporal distribution of GS loading in combined sewerage systems. In: *Ninth International Conference on Urban Drainage, Portland/Oregon, USA*.

Friedler, E. 2004 Quality of individual domestic greywater streams and its implication on on-site treatment and reuse possibilities. *Environmental Technology* **25** (9), 997–1008.

Friedler, E. & Butler, D. 1996 Quantifying the inherent uncertainty in the quantity and quality of domestic wastewater. *Water Science and Technology* **33** (2), 65–78.

Friedler, E., Butler, D. & Brown, D. M. 1996 Domestic WC usage patterns. *Building and Environment* **31** (4), 385–392.

Friedler, E., Kovalio, R. & Galil, N. I. 2005 On-site greywater treatment and reuse in multi-storey buildings. *Water Science and Technology* **51** (10), 187–194.

Friedler, E., Butler, D. & Alfiya, Y. 2013 Wastewater composition. In: *Source Separation and Decentralisation for Urban Water Management* (T. A. Larsen, K. M. Udert & J. Lienert, eds). IWA Publishing, London.

Gato-Trinidad, S., Jayasuriya, N. & Roberts, P. 2011 Understanding urban residential end uses of water. *Water Science and Technology* **64** (1), 36–42.

Gouda, H., Jack, N. & Ashley, R. 2001 Stochastic approach to the modelling of gross solids mass flow in sewer systems. *Specialty Symposium on Urban Drainage Modeling at the World Water and Environmental Resources Congress, Orlando, FL, USA*.

Lange, J. & Otterpohl, R. 2000 *Abwasser: Handbuch zu einer zukunftsfähigen Wasserwirtschaft*, 2nd edn. Mall-Beton-Verlag, Germany.

Langergraber, G., Alex, J., Weissenbacher, N., Woerner, D., Ahnert, M., Frehmann, T., Halft, N., Hobus, I., Plattes, M., Spering, V. & Winkler, S. 2008 Generation of diurnal variation for influent data for dynamic simulation. *Water Science and Technology* **57** (9), 1483–1486.

Littlewood, K. & Butler, D. 2003 Movement mechanisms of gross solids in intermittent flow. *Water Science and Technology* **47** (4), 45–50.

Mattsson, J., Hedstroem, A., Ashley, R. M. & Viklander, M. 2015 Impacts and managerial implications for sewer systems due to recent changes to inputs in domestic wastewater – a review. *Journal of Environmental Management* **161**, 188–197.

Ogurek, M., Alex, J., Rieger, L., Schraa, O. & Schütze, M. 2015 *A Novel Integrated Approach for Designing, Testing and Implementing WRRF Process Control Solutions*. WEFTEC, Chicago.

Penn, R. 2015 *Impacts of On-Site Greywater Reuse and Water Saving on Urban Wastewater Systems – an Integrated Simulation Approach*. PhD Thesis, Technion, Haifa, Israel.

Penn, R., Hadari, M. & Friedler, E. 2012 Evaluation of the effects of GWR on domestic wastewater quality and quantity. *Urban Water Journal* **9** (3), 137–148.

Penn, R., Schütze, M. & Friedler, E. 2013 Modelling the effects of on-site GWR and water-efficient toilets on municipal sewer systems. *Journal of Environmental Management* **114**, 72–83.

Penn, R., Schütze, M. & Friedler, E. 2014 Assessment of the effects of GWR on GS movement in sewer systems. *Water Science and Technology* **69** (1), 99–105.

Penn, R., Schütze, M., Gorfine, M. & Friedler, E. 2017 Simulation method for stochastically generating domestic wastewater discharge and the effect of greywater reuse on gross solid transport. *Urban Water Journal* published online, DOI: 10.1080/1573062X.2017.1279188.

Rodríguez, J. P., McIntyre, N., Díaz-Granados, M., Achleitner, S., Hochedlinger, M. & Maksimović, C. 2013 Generating time-series of dry weather loads to sewers. *Environmental Modelling & Software* **43**, 133–143.

Rossman, L. A. 2004 *Stormwater Management Model. User's Manual. SWMM5.0*. US Environmental Protection Agency.

Schütze, M., Butler, D., Davies, J. W. & Jefferies, C. 2000 Modelling aesthetic pollution in sewers. In: *First International Conference on Urban Drainage on the Internet (ICUDI)*.

Schütze, M., Penn, R., Friedler, E., Gorfine, M. & Alex, J. 2014 Simulation of GS generation and transport in a separate sewer system in Israel. In: *13th IAHR/IWA International Conference on Urban Drainage, Kuching, Malaysia*.

Shteynberg, D. 2015 *Measurement and Simulation of the Diurnal Pattern of Domestic Water Demand on Micro-Component Scale*. MSc Research Thesis, Technion, Haifa, Israel.

Spence, K. J., Digman, C., Balmforth, D., Houldsworth, J., Saul, A. & Meadowcroft, J. 2015 GS from combined sewers in dry weather and storms, elucidating production, storage and social factors. *Urban Water Journal*. Published online, DOI: 10.1080/1573062X.2015.1025081.

Walski, T., Falco, J., McAloon, M. & Whitman, B. 2011 Transport of large solids in unsteady flow in sewers. *Urban Water Journal* **8** (3), 179–187.

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