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Key Points:

- A systematic approach for evaluating effects of transition to water-efficient solutions on sewers is presented
- Transition to water-efficient solutions affects sulphide and sediment accumulation in pipes
- Reduced flows and increased chemical oxygen demand and temperatures affect these accumulations

Supporting Information:

Supporting Information may be found in the online version of this article.

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Effects of Transition to Water-Efficient Solutions on Existing Centralized Sewer Systems—An Integrated Biophysical Modeling Approach

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Abstract Technical alternatives offering high water efficiency are being developed to complement existing centralized water and wastewater conveyance and treatment systems. Understanding of the negative effects wide-spread implementation of such alternative systems may have on existing systems is still limited, despite the importance of this inevitable transition. In this study, we present a novel approach to systematically identify these negative impacts. A comprehensive model integrating transport and transformation processes in sewer pipes was set up and simulated for various transition scenarios. A significant finding of this research is that reduced flows and increased chemical oxygen demand (COD) concentrations result in the accumulation of sediments and sulphides in sewer pipes. For the examined sewer system, when reducing the total daily flow by 50%, 30% of the pipes were found to accumulate sediments, and 30% of the pipes experienced effects due to the presence of sulphides in different states depending on the wastewater temperature. It was found that an optimal spatial distribution of these water-efficient solutions will most likely require compromises between sediment and sulphide accumulation. The product of two design parameters, diameter and bed slope, was found to be a suitable predictor of the potential of a pipe to accumulate sediments. This research provides novel approaches to assessing the feasibility of transition to solutions offering higher water efficiency. The results indicate where the most affected points in the systems are expected to occur and might help in preparing an experimental approach to assess such negative effects, increasing urban water management efficiency.

1. Introduction

Increasing the efficiency of urban water and wastewater systems is a critical challenge for global sustainability. Most affluent cities possess centralized water and wastewater conveyance and treatment systems. These long-lived and investment-intensive centralized systems are subject to changes to their original design specification, as attractive technical alternatives continue to be developed to complement these existing systems. These alternatives include novel systems for drastically reducing domestic water consumption and for decentralized wastewater reuse. Major concerns arise from changes in the specific composition of the wastewater, such as reductions in the amount of water or increases in specific pollutant concentrations. These are expected to affect the operation and maintenance of existing systems. The understanding of these effects is still rudimentary. Therefore, drawing comprehensive conclusions about transition effects and about implementing such a transition on a large scale remains challenging. Hence, investigating transition feasibility and mitigating transition problems is a global challenge gaining the attention of academic and professional circles.

Grant et al. (2012) showed that the introduction of water-saving measures and decentralized wastewater treatment and reuse techniques increases water productivity. They defined water productivity as “the value of goods and services produced per unit of water used.” They focused on three different strategies for improving water productivity: “substituting higher quality water with lower-quality water where appropriate, regenerating higher-quality water from lower-quality water by treatment, and reducing the volume of higher-quality water used to generate goods and services.” Such measures for increasing water productivity may include greywater reuse (substitution), full on-site domestic wastewater treatment and sewer mining (regeneration), and water-efficient domestic appliances including water-efficient toilets (reduction). All these measures, however, might have a negative impact on existing sewer networks.

In many situations, decentralized systems may provide better solutions than existing centralized options (e.g., Marlow et al., 2013). These situations include cases in which flexibility of the systems is desired due to anticipated changes in climate, land use, and demography. For example, the former German Democratic Republic (East Germany) has undergone a profound reduction in population. This phenomenon was not anticipated and hence not taken into consideration when its centralized systems were designed, with a design life-span of 25–50 years (Schlör et al., 2009). More frequently, in many places, the specific amount of water consumption has been reduced due to temporary drought (e.g., the [Target 155 campaign](#), a water efficiency program in Melbourne, Australia; see [Target 155](#)). Therefore, novel technologies to enhance water productivity and consequently reduce net domestic water consumption are extensively promoted in many countries (e.g., Guo & Englehardt, 2015; Larsen et al., 2016). In addition, decentralized systems with lower investment costs may be preferable to expensive rehabilitation of existing centralized systems. Eggimann et al. (2015, 2016) showed that decentralized solutions are more economically feasible under certain conditions than centralized options. When socio-environmental aspects are also considered, the best option will depend on the aims and interests of the system manager (Corominas et al., 2018).

Transition to higher water productivity solutions, especially on large scales, requires that the effects on the existing centralized systems be considered (Mattsson et al., 2015). Such transition influences the quality and quantity of wastewater discharged into existing centralized systems and can negatively affect their operation and maintenance (Penn et al., 2012). Understanding of the quantitative consequences of these effects is still limited, despite the importance of such inevitable transition.

The negative effects of the decrease in wastewater quantity may include accumulation of solids in sewer pipes. These sediments can form blockages and loss of hydraulic capacity, and they can store pollutants and enhance the formation of hydrogen sulphide (H_2S) (Butler & Davies, 2010; Cook et al., 2018; Liu et al., 2015; Marleni et al., 2015; Mattsson et al., 2015; Penn, Schütze, Alex, & Friedler, 2017; Penn, Schütze, & Friedler, 2013; Sitzenfrei et al., 2013). Flow reduction may increase pollutant concentrations. For example, greywater reuse can increase chemical oxygen demand (COD) concentrations by 40% (Penn, Schütze, & Friedler, 2013; Penn et al., 2012). The sediments may further increase with higher reduction in flows and discharge of sludge from onsite treatment into sewers. Moreover, toilets are the main contributors of total suspended sediments (TSS), total nitrogen (TN), and total phosphorus (TP) to domestic wastewater (Friedler, 2004); hence, incorporating dry toilets (i.e., toilets that recover all their resources) also significantly change wastewater composition. These changes affect the composition of the influent to wastewater treatment plants (WWTP) (Penn, Schütze, Alex, & Friedler, 2017).

The movement and deposition of sediments in sewer pipes are a complex process and depends on the physical and chemical characteristics of the sediment, the velocity and variability of the flow, and the layout and geometry of the drainage network (Butler & Davies, 2010). The interaction between sewage flow and solids movement, together with the complex interrelationships between the solids and their general heterogeneity, render the precise description of solids transport processes challenging (Ashley et al., 2004). Two simple criteria, minimum bed shear stress and minimum velocity, have been defined for self-cleansing designs of sewers in different countries (Ashley et al., 2004). Minimum velocity alone, when unrelated to the characteristics and concentration of the sediment or to other aspects of the hydraulic behavior of the sewer, does not properly represent the ability of sewer flows to transport sediments (Butler & Davies, 2010). In many cases, this criterion has been replaced by minimum bed shear stress, which considers the high variability in sewer flow conditions.

Transitions to water-productive solutions are also expected to increase sulphide-related problems due to increased sedimentation and organic concentrations (Hvitved-Jacobsen et al., 2013; Liu et al., 2015; Melbourne and Metropolitan Board of Works, 1989). These problems are also expected to worsen with increases in temperatures, decreases in flow velocities, and decreases in the presence of electron acceptors such as oxygen (Melbourne and Metropolitan Board of Works, 1989).

The presence of hydrogen sulphide in sewers is associated with health-related effects, odor problems, and concrete and metal corrosion. These are caused by the release of volatile substances in the gas phase and from there into the environment. Volatile substances in sewers include hydrogen sulphide, volatile sulphur compounds, and nitrogen compounds produced under anaerobic conditions in wastewater, biofilms,

and sediments (Hvitved-Jacobsen et al., 2013). Sulphides are produced in the biofilm and in sewer sediments. If sediments are permanently present, they can dominate sulphide production (Hvitved-Jacobsen et al., 2013). The corresponding concentration in the water phase is then a consequence of diffusion from the biofilm and sediment. In general, the literature indicates that dissolved sulphide concentration is associated with potential problems of malodors, health, and corrosion (Hvitved-Jacobsen et al., 2013). Corominas et al. (2018) showed that hydrogen sulphide emissions should be considered in life cycle analysis when assessing decentralization.

As evident from the above survey, some work has been done to characterize the potential effects of changes in wastewater quantity on the accumulation of solids in sewers. To the best of our knowledge, however, no one has yet attempted to explore the negative impact of widespread and systematic implementation of water productivity measures on entire sewer systems. Large-scale measurements of the outcomes of transition scenarios over an extended period of time do not exist. Measurements of real systems are extremely costly due to the long timespans and the extensive measurements needed to uncover these effects.

Hence, the objective of this integrated model-based study is to systematically identify and quantify the effects that transitioning to higher water productivity may have on existing sewer systems. It is important to emphasize that the aim is to create a decision support instrument, based on current best knowledge that indicates potential breaking points in transition scenarios—and not a perfect prognosis tool.

A comprehensive sewer model integrating stochastic generation of domestic wastewater discharges, flows and pollutant transport, sediment accumulation and the formation of sulphides was set up. A sewer system in the coastal area of Israel was used as a case study. Various increased water productivity scenarios were simulated and analyzed. The generated flows (without transition implementations) were validated for the specific case study. The dynamic biochemical transformation models used in this work were validated for diverse case studies (without transition implementations), and typical parameter values were used. Transition scenarios were then simulated while modifying the values of the models' sensitive parameters (flow, temperature, and organic matter; Hvitved-Jacobsen et al., 2013). The results indicate where the most likely to be affected points in the systems are expected to occur, thereby offering valuable support in preparing an experimental approach to assess such negative changes in water productivity.

2. Methods

2.1. Simulation Platform

The simulation platform used for the research was SIMBA#2, an integrated simulator for sewer systems, WWTPs, and river water quality (Alex et al., 2013; Ifak, 2013). An integrated simulation platform combining stochastic generation of domestic wastewater discharges, simulations of flows, pollutant transport, sediment accumulations, and biochemical transformation processes was set up. Two forms of modeling were applied: Hydrodynamic modeling of sewer flows was applied, from which shear stresses, indicating whether a pipe will accumulate sediments, were derived. For simulating the biochemical processes, integration of nonlinear cascades for sewer flows with a series of continuously stirred tank reactors (CSTR) was applied. These are explained in more detail below.

For the investigation of sediment accumulation (see also Section 2.6), the entire system was simulated using the SIMBA# hydrodynamic module. This module is based on an extended version of the US-EPA SWMM (Storm Water Management Model; Rossman, 2004, USEPA website). The dynamic wave routing approach in SWMM was implemented. It solves the complete form of the conservation of mass and momentum equations, for gradually varied unsteady free surface flow, that is, the Saint-Venant differential equation. It couples together a solution for water depth at nodes and flows in pipes. Both variables are time and space (i.e., distance in the pipe) dependent. The water depth in the pipe is then translated as the average of the water depth in its up- and downstream nodes. The implicit backwards Euler method (Ascher & Petzold, 1998) is used for the numerical solution of the differential equations. The Manning's equation is employed to relate flow rate to flow depth and friction slope. Detailed properties of sewer flows, including flows, velocities, and water depths in the pipes and water head in the nodes, allow diurnal patterns of shear stress to be calculated and locations of sediment accumulations to be derived. One of the advantages of the dynamic wave routing

Table 1
Biochemical Processes Incorporated in the Model

r_{grw} —aerobic growth in the bulk water
r_{maint} —maintenance energy requirement
r_a —sulphide formation at the surface of the biofilm
r_d —anaerobic decay of heterotrophic biomass
r_{H_2S} —production of sulphide in the sediment
r_{hydml} —aerobic hydrolysis (fast)
r_{hydms} —aerobic hydrolysis (slow)
r_{rea} —reaeration
r_{grf} —aerobic growth in the biofilm
r_{SIIb} —biological oxidation of sulphide in the water phase
r_{SIIc} —chemical oxidation of sulphide in the water phase
r_{SIIoxf} —biological oxidation of sulphide in the biofilm
r_{fer} —fermentation
$r_{hydrann1}$ —anaerobic hydrolysis (fast)
$r_{hydrann2}$ —anaerobic hydrolysis (slow)

approach is that it provides attenuation of flows. Peak flows are responsible for the movement of the solids; hence their attenuation affects the predictions of whether a pipe accumulates sediments or not.

The dynamic biochemical transformation processes (see also Section 2.7 and the Supporting Information) were simulated using the “Lagrange block” option in SIMBA#. Using the SWMM module within SIMBA# enabled us to also to model the biochemical processes; however, in this application, each pipe is modeled as one CSTR. By using the “Lagrange block,” each pipe is modeled as a series of CSTRs in which the complex quality processes are modeled using the Petersen-Gujer matrix (Gujer, 2008). In this application, sewer flows can be modeled by either a series of nonlinear cascades or by the diffusion wave approximation of the Saint-Venant equations. Both methods provided similar results. Therefore, the former was chosen due to its shorter simulation time. Numerical simulations estimated the diurnal variations in the following state variables: fermentable readily biodegradable substrate, fast and slow biodegradable hydrolyzed substrate, heterotrophic active biomass, sulfate and sulphide in the water phase, and dissolved oxygen. The detailed transformation model is presented in Tables 1–3 below and Tables S1–S6. The number of CSTRs and cascades into which a pipe was divided was determined by its length, corresponding to 30 m for each CSTR or cascade. This value was found to provide the best compromise between high numerical accuracy and reasonable simulation time (Sharma et al., 2008). To reduce simulation time, pipes with identical diameters, similar bed slopes, and no additional wastewater input were clustered into single, longer pipes. The number of nonlinear cascades and CSTRs into

which each longer pipe was divided was suited to its length, keeping the 30 m length for each cascade and CSTR. Comparison of simulation results from the detailed model with those from the clustered longer pipes verified that this step did not reduce the accuracy of the simulation results. Simulation results included flow properties and concentrations of the base scenario (Table 4); results not shown.

2.2. Case Study of a Separate Sewer System

A separate sewer system in a densely populated neighborhood located in Netanya, a coastal city in Israel, served as a case study. The neighborhood covers an area of $\sim 1.3 \text{ km}^2$, accommodating some 15,000 residents living in multiple-flat buildings. The sewer system is composed of 154 nodes and 153 pipes, with diameters ranging from 0.15 (upstream pipes) to 0.45 m (downstream ones) and an overall length of about 6 km. Figure 1 presents the layout of the modeled sewer network. Buildings were aggregated into 34 clusters, each discharging wastewater into a single node. To simulate effects on downstream segments of the sewer system (i.e., segments adjacent to the WWTP), a long downstream segment (5 km, diameter of 450 mm and bed slope of 0.74%) was artificially added to the existing system. Further information on the case study site can be found in Penn, Schütze, and Friedler (2013).

2.3. Stochastic Input to the Model

Diurnal patterns of quality and quantity discharged from single households were derived from a stochastic wastewater generator (Penn, Schütze, Gorfine, & Friedler, 2017). An Israeli data set of an end-use (individual domestic appliances) water usage measurement campaign (Shteynberg, 2015) was used as input data to the generator. The generator considers dependencies between household size and water consumption, in-house water-use events, and the nonlinear dependencies between household size and the variations in water usage patterns and quantities. The flows for each household were generated by a sampling procedure from the data set. Wastewater is discharged from households by short pulses. When the flow from various houses is combined, it becomes more continuous, and attenuated (Butler & Davies, 2010). During the night there are time periods in which wastewater does not flow in the pipes. An example is presented in Figure S1. The average wastewater discharge was 123 L/PE/d. The generated flows were validated for the represented sewer system, by sewer flow measurements (Penn, Schütze, Gorfine, & Friedler, 2017). COD

Table 2
The Petersen-Gujer Matrix of the Biochemical Processes Incorporated in the Model

	S_s	XS_1	XS_2	XBH_w	SH_2S_{aq}	SSO_4	SO
r_{grw}	$-1/YHw$	0	0	1	0	0	$-1*(1-YHw)/YHw$
r_{grf}	$-1/YHw$	0	0	1	0	0	$(YHf-1)/YHf$
r_{maint}	-1	0	0	-1	0	0	-1
r_{hydrn1}	1	-1	0	0	0	0	0
r_{hydrn2}	1	0	-1	0	0	0	0
$r_{hydrann1}$	0.74	-1	0	0	0	0	0
$r_{hydrann2}$	0.74	0	-1	0	0	0	0
r_{fer}	-0.48	0	0	0	0	0	0
r_{rea}	0	0	0	0	0	0	0
r_d	0	0	1	-1	0	0	0
r_a	0	0	0	0	1	-1	0
r_{SIIc}	0	0	0	0	-1	1	$-1/Rcwc$
r_{SIIb}	0	0	0	0	-1	1	$-1/Rcwb$
$r_{rSIIoxf}$	0	0	0	0	-1	1	$-1/Rcfb$
r_{H_2S}	0	0	0	0	1	-1	0

concentrations were extracted from Friedler et al. (1996), Almeida et al. (1999), and Friedler (2004). The average concentrations implemented were: 1,340, 1,339, 386, 230, 641, 658, 3,972, 1,296 mg/L for kitchen sink, washing machine, washbasin, bathtub, shower, half flush toilet, full flush toilet, and dishwasher. Patterns were generated for seven weekdays, in total, for the base scenario, in which no changes in wastewater quality and quantity were made. To evaluate the uncertainty in model predictions seven weekdays were generated. Weekends demonstrate different diurnal patterns and were not considered in this study. Diurnal input patterns for the other scenarios were derived by modifying these base scenario patterns as described

Table 3
Fractions of the Biochemical Processes

Fraction name	Description	Unit
S_s	Fermentable, readily biodegradable substrate	$gCOD/m^3$
XS_1	Hydrolyzed substrate, fast biodegradable	$gCOD/m^3$
XS_2	Hydrolyzed substrate, very slowly biodegradable (includes inert)	$gCOD/m^3$
XBH_w	Heterotrophic active biomass in the water phase	$gCOD/m^3$
SH_2S_{aq}	H_2S and HS^- in the water phase	$gCOD/m^3$
SSO_4	Sulfate concentrations in the water phase	gS/m^3
SO	Dissolved oxygen	$gCOD/m^3$

Table 4
Definitions of the Different Scenarios Considered

Flow (Q)	COD	1.5COD	2COD	4COD
Q	1	12	18	24
0.9Q	2			
0.7Q	3			
0.5Q	4			
0.3Q	5			
0.1Q	6			
~0.9Q	7	13	19	25
~0.7Q	8	14	20	26
~0.5Q	9	15	21	27
~0.3Q	10	16	22	28
~0.1Q	11	17	23	29

Note. The scenario number is based on variation of the flow Q (lines) and the concentration (chemical oxygen demand [COD] in the wastewater, columns). 0.9Q means that the flow of the base scenario is reduced by 10%. The ~ is used since in these scenarios the peaks were reduced and the overall reduction is almost the same as in scenarios 2–6, for example, ~0.9 refers to a 12.9% reduction. 1.5COD means the COD concentration of the base scenario is increased by 1.5.

below and in Table 4. An example of the diurnal patterns of wastewater discharged into pipe 36, for the various scenarios simulated, can be found in the Supporting Information.

2.4. Scenarios Simulated

The scenarios that were simulated are summarized in Table 4. In scenarios 2 to 6, the flows were reduced by 10%, 30%, 50%, 70%, and 90% of the total daily discharge. The reduction was distributed uniformly across the day and attributed to all the houses in the catchment area. These general scenarios enable an assessment of the performance of the system without considering specific transition technologies. Implementing greywater reuse for toilet flushing and garden irrigation does not distribute reduction of wastewater flows evenly throughout the day but instead impacts peak usage (Penn et al., 2012). To mimic such a phenomenon, the peaks were also reduced. The n highest peaks in one simulation day were detected. Their value was reduced to that of the lowest of these peaks. The value of n was different for each scenario and equaled the appropriate percentage of reduction in flow. This procedure enabled us to maintain a similar overall daily reduction in flows of 12.9%, 34.3%, 54.5%, 73.7%, and 91.6% of the total daily flow in scenarios 7–11, respectively.

Various scenarios in which COD concentrations in the wastewater were increased were simulated to investigate the effects of the increase in COD concentrations on the biochemical processes. This follows the findings that with greywater reuse, COD concentrations may increase by 40% (Penn, Schütze, & Friedler, 2013). To also consider more extreme future scenarios, higher increases in concentrations were considered. COD concentrations affect the formation of hydrogen sulphide, which is also highly affected by the accumulated sediments. Analysis of sediment accumulation in the pipes indicated that reduction of peaks significantly affects the accumulation of sediments in the sewer pipes (see the Section 3). Hence, the patterns generated for scenarios 7–11 were further modified to investigate the effects of increased COD concentrations on the biochemical processes in the sewer. In scenarios 12–17, COD concentrations were increased by a factor of 1.5 compared to the corresponding scenarios (1 and 7–11) and by 2 and 4 in scenarios 18–23 and 24–29, respectively.

Each scenario was simulated for seven weekdays to analyze the effects on different days (stochastically generated). Weekend days were not considered. Additionally, all scenarios were simulated for three characteristic wastewater temperatures: 10°C (e.g., northern Europe; Butler & Davies, 2010), 20°C (e.g., summertime in northern Europe; Butler & Davies, 2010), and 30°C (e.g., summertime in warm countries, from measurements performed by the authors).

2.5. Stream Order as a Means to Map the Effects in the Sewer

The stream order is a positive whole number and indicates the location of a pipe in a sewer system. The stream orders of the pipes, following Strahler (1952), can be seen in Figure 1.

2.6. Inference of Sediment Accumulation in the Pipes

Due to the high ambiguity of models predicting sediment accumulation in pipes (Ashley et al., 2004), predicting the exact location, quantity, and quality of the sediments remains uncertain. A more general approach using a single critical value, bed shear stress, was hence implemented to determine whether a pipe accumulates sediments or not.

Figure 1. Layout of the case study (separate sewer, based on Penn, Friedler, & Ostfeld, 2013).

According to Vongvisessomjai et al. (2010), part-full flow sanitary sewer pipes should be designed so that the minimum bed shear stress exceeds 2 Pa. Babaeyan-Koopaei et al. (1999) showed, in laboratory experiments, that a gross solid will only move if both water velocity and water level exceed a certain threshold. Their results were confirmed by a regression analysis by Schütze et al. (2000). Experiments in real sewer pipes revealed that the critical velocity and relative water depth, needed for the transport of gross solids, should be 0.23 m/s and 0.1333, respectively (Penn et al., 2018). Shear stress, flow velocity, and relative depth were all used to determine whether a pipe accumulates sediments. The critical shear stress was increased to 3 Pa to ensure wash-off of stationary sediments.

To obtain a consistent single indicator, the critical water depth and velocity were transformed into the appropriate shear stress. These shear stresses were unique to each pipe depending on its diameter and slope. Hence, each pipe had three critical shear stresses. The highest of these three values was then designated as the critical indicator for each pipe, allowing us to determine whether sediments accumulate in it. The numerical model simulates non-uniform flow along the pipes and calculates the diurnal patterns of flow velocities and water depths in the pipes (as mentioned in Section 2.1, the water depth in a pipe is an average of the water depth in its up- and downstream nodes). The critical shear stresses defined from the critical relative depth and from the critical velocity were derived from Equations 1–4. Transforming the critical relative depth (i.e., 0.133) into the critical shear stress was straightforward (Equations 1–3). The critical velocity (i.e., 0.23 m/s) was translated into the appropriate shear stress as follows. The transformation of the flow velocities into shear stress is not straight forward. Nevertheless,

it is easily done from the water depth based on Equations 1–3. Therefore, the time in which wastewater velocity reached the critical velocity value was determined from simulation results. The water depth corresponding to that time, which was different for every pipe, was then used to calculate the critical shear stress (Equations 1–3).

$$\tau_{crit,d/D} = \rho \cdot g \cdot R_h \cdot S, \quad (1)$$

where $\tau_{crit,d/D}$ is the bed shear stress (Pa), ρ is the density of water (1,000 kg/m³), g is the gravitational acceleration (9.8 m/s²), R_h is the hydraulic radius (m), and S is the friction slope (m/m).

Friction slope was derived by subtracting the water head in the up- and downstream nodes and dividing this result by the horizontal distance between each end of the pipe.

$$R_h = \frac{A}{P} = \frac{r^2(\theta - \sin(\theta))/2}{r \cdot \theta} = \frac{D(\theta - \sin(\theta))}{4\theta}, \quad (2)$$

where A is the cross sectional area of the pipe (m²), P is the wetted parameter (m), r is the pipe radius (m), D is the pipe diameter (m).

$$\theta = 2 \cdot \cos^{-1}\left(\frac{r-d}{r}\right), \quad (3)$$

where d is the water depth (m).

$$d = d^* \cdot D, \quad (4)$$

where d^* is the critical relative depth (0.133) and D is the pipe diameter (m).

Once the value of the critical indicator for each pipe was determined, it was compared with the diurnal patterns of the shear stress in each scenario. A pipe was then categorized as a sediment-accumulating pipe if the shear stress did not reach this critical value during the seven-day simulation. Diurnal patterns of shear stresses in the pipes were derived from water depth, obtained from the hydrodynamic simulations of the flows (Equations 1–3).

Equations 1–3 demonstrate a relation between shear stress, diameter, and friction slope. As can be seen from Equation 3, θ is constant for a specific relative depth: d/D . Combining this realization with Equations 1 and 2, the shear stress will then be equal to a variable ($(\theta - \sin(\theta))/\theta = \theta^*$) multiplied by the product of the diameter and the slope (Equation 5). We denote this product as SD .

$$\tau = \rho \cdot g \cdot \theta^* \cdot S \cdot D. \quad (5)$$

According to Equation 5, the critical shear stress, determined from the critical relative depth, increases with higher SD . Hence, it seems plausible that a pipe with high SD is more likely to accumulate sediments. This relation is not obvious in pipes in which the critical indicator was determined according to the wastewater velocity or the recommended shear of 3 Pa. Nevertheless, the diameter and slope influence the shear stress and hence the accumulation of sediments in the pipes. The option of using SD as a simplified indicator of a pipe that will likely accumulate solids, which does not require detailed hydrodynamic simulations of the flows, was, therefore, examined. Accordingly, the friction slope was replaced with the bed slope. Regression was used to calculate the strength of the effect of SD on the potential of a pipe to accumulate sediments. A logistic regression for binary data (in this case, whether a pipe accumulates sediments or not, assigned as 1 and 0, respectively) was used to estimate whether a pipe will accumulate sediments (Venables & Ripley, 2002). Flow reduction and SD were used as explanatory variables (Equation 6).

$$y = g(\beta_0 + \beta_1 \cdot D \cdot S + \beta_2 \cdot Q_{rem}), \quad (6)$$

where y is the probability for a pipe to accumulate sediments, g is the inverse of the logistic function that brings the value of the linear predictor to be between 0 and 1, β_0 , β_1 , β_2 are the parameters of the regression, and Q_{rem} is the proportion of the flow that remains after its reduction.

Dependency on the stream order, an indicator of the location of the pipe in the network, was also examined. It was found not to be statistically significant and so is not included in Equation 6. The results show that in all scenarios, most pipes that accumulated sediments were located upstream (i.e., low stream order). The number of pipes of a specific stream order that accumulate sediments relative to the total number of pipes in that stream order, however, was only slightly higher in upstream pipes than downstream pipes (i.e., high stream order). This is because the number of pipes that are located upstream is much higher than those located downstream.

Uncertainty analysis for the proportion of pipes that accumulate sediments was performed. The proportion of pipes accumulating sediments was calculated for each of the seven simulated days. This was calculated from the stochastically generated diurnal wastewater discharges patterns. The uncertainty interval for each scenario was generated from the seven simulated days.

2.7. Inference of Production of Sulphides and Removal of Biodegradable Organic Matter

The dynamic biochemical process model is based on the WATs approach (Wastewater Aerobic/anaerobic Transformations in sewers introduced by Hvitved-Jacobsen et al., 2013). It includes aerobic growth in the bulk water, aerobic growth in the biofilm, maintenance energy requirement, fast and slow aerobic and anaerobic hydrolysis, fermentation, reaeration, anaerobic decay of heterotrophic biomass, sulphide formation at the surface of the biofilm and sulphide formation in the sediments, chemical and biological oxidation of sulphides in the water phase, and biological oxidation of sulphides in the biofilm. Rates and typical parameter values for the aeration were taken from Lahav et al. (2006), for the production of sulphides in the sediment from Liu et al. (2015), and for the other processes from Hvitved-Jacobsen et al. (2013). A detailed description of the model is given in Tables 1–3 and in the Supporting Information. Many rates are dependent on the ratio of the wetted parameter and cross-sectional area of the flow, where water depths are very low, and this ratio reaches extremely high values, causing unreasonably high rates with corresponding computational problems. To overcome this phenomenon, a threshold water depth of 7 cm was set, as lower values caused numerical errors. In lower water depths, this ratio was kept constant and equal to the value corresponding to 7 cm. The full Petersen-Gujer matrix with all rate equations and parameter values can be found in the Supporting Information.

Total dissolved COD in the domestic wastewater was fractionated into biodegradable organic matter (Ss 22.2%), hydrolyzable substrate (fast biodegradable XS_1 14% and slow biodegradable XS_2 43%), heterotrophic biomass in the water phase (XBH_w 10%), and inert matter (10.8%). The fractionation properties are typical for modeling wastewater processes in sewers (Hvitved-Jacobsen et al., 2013). Typical concentrations of dissolved oxygen (SO), sulfate (SSO_4), and sulphides ($SH_{2,aq}$) were 5 mgO/L, 25 mgS/L, and 0.01 mgS/L, respectively (Hvitved-Jacobsen et al., 2013). It should be recalled that dissolved sulphide concentrations include H_2S and HS^- (depending on the pH). Its concentration in the wastewater should be set to zero, but for numerical reasons, it was set to a negligible value of 0.01 mgS/L.

The sediment surface area serves as an essential input to the biochemical process model. This value is unknown, hence needs to be estimated. If the sediment were evenly distributed along the pipe, its maximum surface area would be the product of the pipe's diameter by its length. Nevertheless, the high diversity in sewer flows and solids means this homogeneity is not expected to occur. It is reasonable to assume that the solids will deposit close to one another, causing a hilly like deposit. Therefore, to simulate a more pronounced case that is, more likely to resemble real values, the maximum sediment surface area was multiplied by two.

Hvitved-Jacobsen et al. (2013) reported two threshold indicators for dissolved sulphide concentrations at which moderate and extreme problems are expected to occur: 0.5 and 2 mgS/L, respectively. It is not clear whether short-term peaks of sulphides have any effect on sulphide-related problems (Pomeroy, 1970; Sharma et al., 2008). Additionally, one may assume that long periods of bad odors will not be tolerated by residents. Consequently, it was defined that if the concentrations of sulphides exceed these threshold values for a duration of more than an hour a day, and the pipe is expected to have sulphide-related problems.

Uncertainty analysis for the number of pipes in which the threshold indicators were reached was performed for scenario 9 at 20°C. Due to very long simulation times (1 h for one simulation run), only this scenario was analyzed. This scenario revealed a relatively high proportion of pipes in which the thresholds were reached and, therefore, it was chosen for the uncertainty analysis. Monte Carlo error propagation with 100 repetitions was performed. The values for the biochemical transformation model parameters were sampled uniformly from an interval of $\pm 10\%$ of their value (results are presented in Section 3.2).

A hypothesis was formed that the removal of the biodegradable organic matter could be enhanced by the reduction in flows and higher retention time in sewer pipes. In lower flows, water depth decreases, and hence, oxygen concentrations may increase, increasing the aeration rate, which in turn may prevent anaerobic conditions and maintain higher oxidation rates of the biodegradable organic matter. To examine this hypothesis, a very long gravity sewer pipe, with much higher retention time, was added at the outlet of the catchment area. Such a pipe can simulate a long pipe conveying wastewater from the outlet of the sewer system toward the WWTP. The properties of the pipe are detailed in the description of the case study.

3. Results

3.1. Inference of Sediment Accumulation in the Pipes

The results presented in Figure 2a shows, as expected, that the number of pipes that accumulate sediments increases with a reduction in flow. Most of these pipes are located in the upper parts of the examined sewer system. This finding corresponds with previous findings (Mattsson et al., 2015). Pipes located in lower sections of the sewer system convey higher flows, and hence, the accumulation of sediments here is less sensitive to the reduction in flow. In pipes located downstream, however, sediments may also accumulate if the slopes are not high enough. Reduction of the peak flows (i.e., scenarios 7–11) significantly increases the proportion of pipes that accumulate sediments. Since most of the flow reduction very likely has an impact on peak flow, these were the scenarios marked for further analysis.

A critical point from which more than 30% of the pipes accumulate sediments occurred at a reduction of 50% of the total daily flow (when peaks are reduced, scenario 9). Figure 2b shows that in scenarios in which the flow is reduced by 50% of the total daily flow or less, pipes accumulate sediments only if SD is below 0.0032. When flows are reduced by more than 50%, this threshold does not hold so strictly; in other words, a higher percentage of the pipes accumulating sediments are below this threshold, but not all of them. Under these conditions, even in pipes that are characterized by relatively high flows (hence higher diameters) and high bed slopes, the water depth, flow velocities, and bed shear stress are no longer high enough to prevent sediment accumulation. Uncertainty analysis of these findings revealed very low uncertainty intervals (Figure 3a), indicating that even though the diurnal household discharge patterns were significantly different (Penn, Schütze, Gorfine, & Friedler, 2017), the presence or absence of the critical shear stress at one point along the day was not significantly different between the stochastically generated patterns.

The logistic regression model confirms the observed trends and shows that SD is a suitable predictor for the potential of a pipe to accumulate sediments. The regression revealed that the probability of a pipe accumulating sediments depends on the reduction in flow and SD. The parameters values were 4.476, $-8.838 + 02$, and $-6.241e-02$ for β_0 , β_1 , and β_2 , respectively. These values show that the higher the SD is and the lower the reduction in the flow (i.e., corresponds to a higher proportion of flow that is not reduced), the lower is the probability that the pipe will accumulate sediments. Both effects were found to be statistically significant, using the Wald test, which is based on the assumption that the parameters are asymptotically normal distributed (low p -values of $<2e-16$, $1.81e-11$, and $<2e-16$ for β_0 , β_1 , and β_2 , respectively; they were tested for their significant difference from zero). The results showed a residual deviance of 318.74 with 448 degrees of freedom, which is an approximated fit of 71%. In 84% of the observations, the model predicted the presence or absence of accumulation correctly.

It should be recalled that the critical SD value of 0.0032 and parameter values of the logistic regression model are applicable only for the sewer system examined with its respective specific configuration. In this system, ranges of bed slopes are 0.0025–0.0476 m/m, diameters are 0.15–0.45 m, and SD are 0.0011–0.0138 m.

Figure 2. (a) Proportion of the pipes that accumulate sediments in each simulated scenario. Each color in a bar corresponds to a stream order. Scenarios marked with a brown rectangular are those in which peak flows were reduced. (b) Binary plots of pipes accumulating sediments or not depending on the product of the diameter $\times$ bed slope. Each subplot is for a different scenario. Each dot refers to a SD value for each pipe in the network.

Verification is needed for other sewer configurations. Nevertheless, these values, once verified, can be used as a warning indicator for hotspots in which solids may accumulate.

3.2. Inference of Production of Sulphides and Removal of Biodegradable Organic Matter

The proportions of pipes reaching the critical concentrations of sulphides are presented in Figure 4. Figure 4a shows that the higher threshold of 2 mgS/L is exceeded in 30% of the pipes, mostly in the extreme scenarios. At 30°C, this point was reached when COD concentrations were four times higher than in the

Figure 3. Boxplots of uncertainties intervals. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Outliers are plotted individually using the “+” symbol. (a) Uncertainty intervals of the proportion of pipes that accumulate sediments in all scenarios simulated. Scenarios marked with a brown rectangular are those in which peak flows were reduced. (b) Uncertainty intervals of the proportion of links in scenario 9 at 20°C in which sulphides were higher than 0.5 mgS/L and higher than 2 mgS/L for more than 1 h a day.

base scenario 1. When flows were reduced by 30%, 50%, and 70%, this point was reached with an increase in COD of 2, 1.5, and 1, respectively. This critical point was also reached at 20°C and 10°C with a high reduction in flows of at least 70% (0.3Q). With such a high reduction in flows, no additional increase in COD was needed.

The point at which 30% of the pipes reached the threshold of >0.5 mgS/L was observed much more frequently. For water temperature of 30°C, this point was reached in all scenarios. For 20°C, this point was reached when COD concentrations were increased, for all households, by at least 1.5. When flows were reduced by 50%, this point was reached without any increase in COD. At 10°C, this critical point was reached in more extreme cases, with a fourfold increase in COD concentrations and flow reduction of 30% (0.7Q). At 70% reduction in flows, the critical point was reached without any increase in COD concentration. All these conditions are summarized in Table 5. Uncertainty analysis of these findings revealed relatively low uncertainty intervals. In scenario 9 at 20°C (Figure 3b), the 25th and 75th percentiles of the proportion of pipes reaching the threshold of 0.5 mgS/L were 0.28 and 0.36, respectively. The 25th and 75th percentiles of those reaching the threshold of 2 mgS/L were 0.18 and 0.21, respectively. The results presented in Figure 4 fall within this range. Figure 4b shows that the pipes reaching the threshold of >0.5 mgS/L are located in upper and lower sections of the network. This is in contrast to the sediment distribution, which was found to accumulate mostly in the upper parts of the sewer network, and despite the fact that sediments in sewers produce a large quantity of sulphides.

Figures 5 and 6 present diurnal patterns of sulphide and oxygen concentrations in pipes along five different paths, each path in a different subplot. The patterns are simulation results of scenario 9 with a 50% flow reduction and no increase in COD. Other scenarios showed similar trends. The momentary concentrations are load-based averages over the seven simulated days. It can be seen that sulphide concentrations increase significantly in pipes in which sediments accumulate and that have low oxygen levels, for example, pipe 109. Pipes located downstream of that pipe, if they do not contain sediments, have reduced sulphide concentrations due to oxidation, for example, pipe 72. If the retention time in the pipe is long enough, the sulphides are significantly oxidized even if oxygen concentrations are low: for example, pipe 74, which

Figure 4. Proportion of the pipes in which sulphide concentrations reach a critical value. (a) The critical value is concentrations above 2 mgS/L (a1) or 0.5 mgS/L (a2) for more than an hour a day. All scenarios are presented for all three simulated temperatures. (b) The critical value is 0.5 mgS/L for more than an hour a day. All scenarios presented were simulated at 20°C.

is the very long pipe added to the outlet of the sewer catchment. In upstream pipes that accumulate sediments, sulphide concentrations do not reach very high concentrations. The high oxygen concentrations lead to high sulphide oxidation rates, for example, pipes 47 and 134 (see Supporting Information for the rate equations). In the pipes located downstream of these pipes, the sulphide concentrations are generally low due to oxidation and dilution from additional inflows with low sulphide concentrations (for example, pipe 135). The growth of biofilms on submerged areas of the sewer pipes is an additional contribution to sulphide production. In this study, the biofilm size was considered by the ratio of the wetted and cross-sectional areas (Hvitved-Jacobsen et al., 2013).

The daily reduction in biodegradable organic matter in the long artificial sewer pipe located downstream (pipe 74) is presented in Table 6 as a percentage. The shortest flow time in the pipe (i.e., corresponding to the maximum diurnal velocity) ranged from ~2 h in the base scenario to ~3 h in the scenario with the highest reduction in flows. With a 70% reduction in flows, a significant reduction of at least 20% in its loads could be reached. This reduction is about two times higher than the expected reduction in the base scenario. When the temperature was 30°C, a 40% reduction was observed. When flows are reduced by 90%, almost 50% can be removed at 20°C. The removal rates of the biodegradable organic

Table 5
States in Which 30% of the Pipes Experienced Sediment Accumulation and Sulphide Concentrations >0.5 mgS/L

Temperature	Accumulation of sediments	Sulphides >0.5 mgS/L ^a	
	Reduction in total daily flows (%)	Reduction in total daily flows (%)	Increase in COD concentrations (%)
10°C	50	30	300
		70	0
20°C	50	0	50
		50	0
30°C	50	0	0

^aEffects due to the presence of sulphides are seen when both states of reduction in flow and increase in chemical oxygen demand (COD) occur.

matter decrease with increasing COD concentrations. With an increase of only 1.5 in COD concentration and reductions in the daily flow of 70% and 90%, the removal rate of the biodegradable matter increases by ~6% and ~20%, respectively, at 20°C.

4. Discussion

The results presented above are based on an integrated model that draws on the current best knowledge of physical and biological processes in sewer systems. It enables us to examine the effects and consequences of dramatic changes in the catchment of sewers, sparing the need to conduct experimental measurements that will be unable to quantify these effects realistically. The decision support instrument that was created indicates potential breaking points in transition scenarios.

The detailed investigation of the case study shows the potential of the modeling tool. As expected, with a decrease in net water use, the wastewater flows in the sewers decrease, which in turn increases sediment accumulation in the pipes. The sediment seems to accumulate predominantly in the upper sections of the sewer network. Not surprisingly, the number of potentially problematic conduits increases with stronger changes in flows. These findings strengthen those of previous studies (e.g., Mattsson et al., 2015; Penn, Schütze, Alex, & Friedler, 2017). More importantly, however, even small changes in the diurnal peak flow pattern can have substantial effects on sediment accumulation.

SD (bed slope*diameter) was found to be a suitable predictor of the potential of a pipe to accumulate sediments. The significance of this finding is that hotspots for potential sediment accumulation can be identified purely by the system's design parameters. This eliminates the need to conduct complex simulations of the system. Other individual parameters such as bed slope, diameter, and stream order were found to be unsuitable as predictors.

In contrast to sediment accumulation, negative effects due to sulphides are more likely to occur in lower sections of the sewer system. Sediments significantly contribute to the formation of sulphides. The contribution is much more substantial in pipes located downstream where oxygen levels are low. This finding falls well within results presented by Liu et al. (2015), who investigated the formation of sulphides and methane in sewer sediments. It is also strengthened by Jin et al., 2018, who showed that sulfate-reducing bacteria (generation of hydrogen sulphide) were found mostly in downstream locations of a pilot sewer system. Issues with sulphides are expected with the increase in concentrations of dissolved COD and with higher temperatures. This aligns with the findings of, for instance, Hvitved-Jacobsen et al., 2013, who pointed out that sulphide problems are expected to worsen with increases in temperature, sediments, and organic matter and with decreases in flow velocities and oxygen. The modeling results indicate that sulphide production is highly temperature-sensitive and might, therefore, also be influenced by urban heat island effects or other climate change phenomena.

Sediments and sulphides are expected to accumulate in different locations of the sewer system. A compromise between these two effects will, therefore, need to be made to achieve optimal spatial distribution of higher water productivity solutions in existing systems. Reductions in wastewater flow and increases in COD concentrations can lead to extreme conditions. The conditions under which sulphide accumulation created problems in 30% of the sewer pipes were different than the conditions creating sediment accumulation problems in the same proportion of pipes. These findings emphasize that the compromise mentioned above needs to be made only in cases where both effects are substantial. At moderate temperatures (20°C) and with a reasonable increase of 50% in COD concentrations, this occurs when daily flows are reduced by at least 30%, whereas sediment problems occur in more than 30% of the pipes when flows are reduced by just 50%. Various strategies can be employed to control sulphide and sedimentation problems. These include injections of chemicals such as oxygen, nitrate, and metal ions for sulphide problems and flushing with pressurized water or air for sedimentation problems.

Substantial removal of biodegradable organic matter was observed in a long gravity pipe segment conveying wastewater from the outlet of the sewer system toward the WWTP. This effect was observed when the flow discharges were reduced by >70% (at 20°C and above). Nevertheless, it is still unknown how substantial this effect is on the WWTP—whether it will have negative effects on biochemical nitrogen removal, or

Figure 5. Diurnal patterns of sulphide concentrations in scenario 9 (50% reduction of flows) at 20°C. In each subplot, the pipes presented follow different paths along the sewer. In the legend of each subplot, the most upstream pipe in the path is at the top of the list. Pipe 74 is located the farthest downstream in the network and is presented in all subplots at the bottom of the legend list. The pipes that accumulate sediment in this scenario are marked with a red rectangular in the subplot's legend list.

Figure 6. Diurnal patterns of oxygen concentrations in scenario 9 (50% reduction of flows) at 20°C. In each subplot, the pipes presented follow different paths along the sewer. In the legend of each subplot, the most upstream pipe of the path is at the top of the list. Pipe 74 is located farthest downstream in the network and is presented in all subplots at the bottom of the legend list. The pipes that accumulate sediment in this scenario are marked with a red rectangular in the subplot's legend list.

Table 6
Daily Load Removal of the Biodegradable Organic Matter in the Long Gravitational Pipe Located Downstream

Reduction in flow	Flow time	Daily loads removed of biodegradable organic matter in the long pipe segment (%)											
		COD			1.5COD			2COD			4COD		
		10°C	20°C	30°C	10°C	20°C	30°C	10°C	20°C	30°C	10°C	20°C	30°C
0	2 h	9.9	11.9	18.4	6.9	8.8	13.5	5.5	7.3	11.5	3.5	5.3	9.0
10%	2.1 h	10.5	12.7	19.5	7.3	9.3	14.5	5.8	7.7	11.8	3.7	5.6	9.3
30%	2.4 h	12.3	15.1	23.0	8.5	10.8	16.4	6.8	8.9	13.4	4.3	6.2	10.2
50%	2.5 h	14.9	18.6	27.5	10.3	13.1	19.3	8.2	10.6	15.9	5.1	7.2	11.8
70%	2.8 h	20.5	26.4	40.2	14.0	17.9	27.0	11.1	14.2	21.5	6.7	9.3	15.4
90%	3.2 h	44.4	48.6	81.5	28.2	31.8	53.8	21.3	24.5	40.8	12.2	15.1	25.4

Abbreviation: COD, chemical oxygen demand.

alternatively, if it will positively affect the pre-treatment of the wastewater before its arrival at the WWTP. These results must be validated experimentally. Further questions as yet unanswered include how much of the operational costs of existing centralized WWTPs can be saved, how much stress can be alleviated from plants reaching their full capacity, and how beneficial these effects are compared to the substantial quantities of sediment and sulphides accumulating in these conditions.

Further research is needed to quantify the model parameters and assumptions made for the model, and these need to be validated by field and laboratory experiments. In addition, results from additional case studies are needed to identify more generalizable conclusions that help to navigate planned or unplanned changes to the wastewater regime. Our results show that SD, the bed slope multiplied by the diameter, might be a good indicator to rapidly assess critical conduits within a catchment area. To examine the soundness of this effect, the ranges of these parameters' values should be extended to represent configurations of other catchment areas. Better predictions of the circumstances under which sediment accumulates and erodes, how it is distributed along sewer pipes, how it may be affected by an increase in particulate COD concentrations, and how the composition of sediment and eroded matter can be characterized are needed. These will enhance the assessments presented in this paper. Validation is further needed for the predictions of the biochemical transformation model that were extrapolated to cases of extreme reduction in sewer flows and an increase in pollutant concentrations. For example, changes in chemical concentrations in the liquid phase of the wastewater may affect the microbial community, which may affect sulphide production.

The results of this research, nevertheless, provide novel assessments of the effects to be expected from implementing solutions offering higher water productivity. To the best of our knowledge, this is the first study to combine the effects of sediment accumulation with the formation of sulphides while analyzing the feasibility of a transition to solutions offering higher water productivity.

5. Conclusions

An integrated model was set up to systematically identify the effects of changes in wastewater quantity and quality on an existing case study sewer system. These changes are expected to occur directly as the result of implementation of decentralized wastewater treatment and reuse systems or spontaneously due to water shortages, climate change, and population changes. The effects found in this work can significantly help investigate the feasibility of transitioning to higher water productivity solutions. The model presented in this work enables in-depth evaluations of the processes that are expected to be influenced by such transitions. It integrates stochastic generation of domestic wastewater streams, hydrodynamic simulations of the flows, transport of pollutants, and their biochemical transformation processes.

The results showed

1. An increased probability of sediment accumulation in the smaller diameter pipes with reduction in flow. At a 50% reduction in the total daily flow, 30% of the pipes were found to accumulate sediments.
2. An increased probability of sulphide production in the larger diameter pipes with the reduction of flow and increase in COD concentrations and in wastewater temperature. The conditions under which sulphide accumulation created problems in 30% of the sewer pipes were different than the conditions creating sediment accumulation problems in the same proportion of pipes (Table 5).
3. An increased probability of the removal of biodegradable organic matter with reduction in flow and with lower concentrations of COD. The removal was reached in a long sewer pipe located at the output of the sewer system. Daily flows were then reduced by 70% and 90%, at which point the removal was 26% and 49% of the daily loads, respectively (at 20°C).

It was found that compromises between sediments and sulphide accumulation will most likely need to be made for optimal spatial implementation, on a large scale, of systems offering higher water productivity.

Further research is needed to substantially quantify and validate the effects found in this work. Its results, however, provide novel approaches to assessing the feasibility of transition to solutions offering higher water productivity. These results can thus contribute to the currently limited understanding of such transitions. It can support their optimal execution, which will promote the design and management of the water-sensitive cities of the future.

Data Availability Statement

Datasets for this research were obtained from Shteynberg (2015) Friedler et al. (1996) Almeida et al. (1999), and Friedler (2004).

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