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Guidelines for capacity reducing gas pockets in wastewater mains

Ivo Pothof[1,2], Michiel Tukker[1], Kees Kooij[1] and Francois Clemens[2]
[1]Deltares, Industrial Hydrodynamics
Delft (Netherlands)
[2]Delft University of Technology, Faculty Civil Engineering, Sanitary Engineering,
Delft (Netherlands)
[1]Ivo.Pothof@Deltares.nl

Abstract

Pressurised wastewater mains in urbanised delta regions include many inverted siphons to cross channels, motorways, railways and other infrastructure. Accumulating gas pockets in these inverted siphons cause significant capacity losses. These gas pockets are responsible for an estimated annual CO_2 release of 10,000 ton in the Netherlands, equivalent to the electric power consumption of 5,400 households. Other consequences of the presence of gas pockets include combined sewer overflows, increased maintenance costs and less reliable operation.

Co-current air-water flow experiments have been carried out with clean water, water with surfactants and with raw wastewater. The research has shown that the air inflow in pumping stations may well exceed the air transport capacity of inverted siphons. Mitigating measures such as deflection plates or optimisation of the switch-off level of pumping stations were proven very effective.

A numerical model for air transport by flowing water has been developed and validated against a wide range of experimental data [1, 2]. Furthermore, the new scientific knowledge and practical experience from the project partners have been incorporated in a new and unique handbook on the hydraulic design and operation of pressurised wastewater mains. The handbook is available via the website (http://capwat.deltares.nl, in Dutch). This paper summarises the scientific results from the research project and their practical consequences for design and operation of (waste)water pipelines.

Keywords
Pipe flow, wastewater, air-water flow, guidelines, hydraulic design

1. INTRODUCTION

Pressurised wastewater mains in highly urbanized (delta) regions include many inverted siphons to cross channels, motorways, railways and other infrastructure. Many of these inverted siphons have been constructed by the horizontal directional drilling (HDD) technique, which has become common practice since the 1990s. Gas pockets accumulate in these inverted siphons causing significant capacity losses and extra power consumption. If the pumps are not blocked, gas pockets in downward sloping sections are the main cause of an increased energy consumption and reduced capacity of pressurized wastewater mains. Air pockets in pressurised wastewater mains often are not expelled via air valves, because:

1. Hazardous gases may be released, which is unacceptable in populated areas,
2. Air valves often do not cope with the composition of wastewater and remain closed or, even worse, remain open after the air has been expelled,
3. Pressure may be sub-atmospheric at the intended air valve location, and
4. Preferred air valve location is on private property or on an inaccessible location for maintenance.

Therefore, air must be transported by the flowing water in many pressurized wastewater mains.

CAPWAT is an abbreviation of *CAPacity reduction and hydraulic losses in wasteWATer mains*. The Joint Industry Project CAPWAT has been mainly funded by the water boards and consultants. Since its start in 2003, CAPWAT consisted of a scientific research track and a practical track. The research track has focused on physical and numerical modelling of co-current flow of air and water in downward sloping pipes. The practical track has focused on the development of new guidelines for the hydraulic design and operational management of wastewater mains. The new guidelines were drafted from the collected knowledge from the participants, literature and a vast amount of new experimental data on the transport and break-down of gas pockets in downward sloping pipes, obtained in the research track.

The set-up of this paper is as follows. Section 2 summarises the various sources of air and gas in pressurised wastewater mains. The key findings of the research track are discussed in section 3, those of the practical track are discussed in section 4. Conclusions are listed in section 5.

2. SOURCES OF AIR IN WASTEWATER MAINS

Gas pockets in wastewater mains originate from a number of sources:

1. free-falling jet in the pump pit,
2. pump stop,
3. leaks,
4. air valves and
5. biochemical processes.

Air may entrain continuously in case the sewer outflow is a free-falling jet into the pump pit [3, 4].

Figure 1: Air entraining plunging jets in the lab [3] and the field

Air may also entrain discontinuously after pump stop if the pump inertia is sufficient to drain the pit down to the bell-mouth level. This kind of discontinuous air entrainment occurs mainly in wastewater systems with a marginal static head. Another transient phenomenon causing an inflow of air, however more unlikely, is a pump trip in a dendritic pressurised wastewater system. The induced transient may suck wastewater from an idle pumping station, causing air entrainment in the idle pumping station.

If the pipeline is subject to negative pressures during normal operation or during transients, then air may be sucked into pipeline via leaks or may enter intentionally via air valves.

Another possible cause of gas pocket development consists of biochemical processes in the pipeline, mainly CO_2, H_2S, N_2 and CH_4. Carbon dioxide and hydrogen sulphide are highly soluble in water. Hydrogen sulphide (H_2S) production is limited by the availability of sulphur-ions (S^{2-}). The design concentration of sulfides in domestic wastewater is 100 mg/ltr [5], from which at most 35.4 mg(H_2S)/ltr may be produced. The solubility of H_2S is temperature dependent (Table 1), but exceeds the dissolved H_2S concentration with a factor 100 or more. Therefore, the partial H_2S pressure in a gas pocket will be at most 1% of the total pressure and hydrogen sulphide may be eliminated from the above list of components in a capacity reducing gas pocket. Analyses of gas samples from long pressurised wastewater mains confirms the dominant presence of methane (CH_4) and nitrogen (N_2) [6].

Table 1: Solubility of hydrogen sulphide in water

Temperature [°C]	Solubility [mg/ltr/bar]
0	6800
13	5100
20	3900
30	3200

3. RESEARCH TRACK

3.1 Approach

The main research question was the development and validation of a total air transport model by flowing water, including the influence of pipe angle, length of sloping section, pipe diameter, surface tension, absolute pressure and viscosity. Furthermore, the air transport and gas pocket head loss in wastewater have been compared with those in clean water. In order to validate the model measurements have been performed in laboratory facilities with internal pipe diameters of 0.08 m up to 0.5 m and in a large-scale facility at a wastewater treatment plant (*D* = 0.192 m ; *L/D* = 209). Pothof performed experiments with raw wastewater and with surfactant-added water in addition to the experiments with clean water [7]. The key elements of the experimental facilities and the concept of the gas pocket head loss measurements are illustrated in the definition sketch (Figure 2).

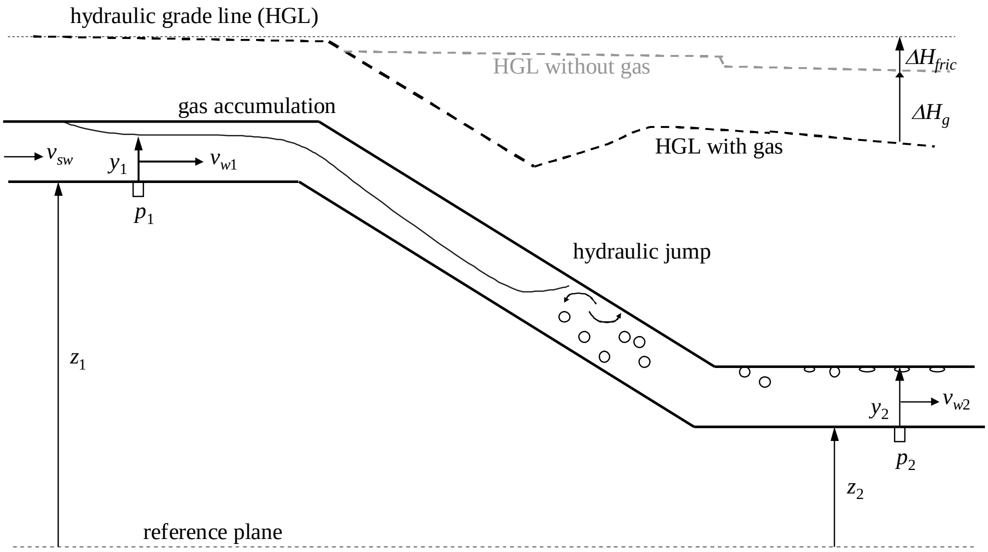

Figure 2: Definition sketch for gas pocket head loss measurements in experimental facilities

3.2 Key results

Under certain conditions up to seven, almost stagnant, air pockets could exist in the downward sloping section of the facility at the WWTP (Figure 3). The available flow regime descriptions have been extended and detailed.

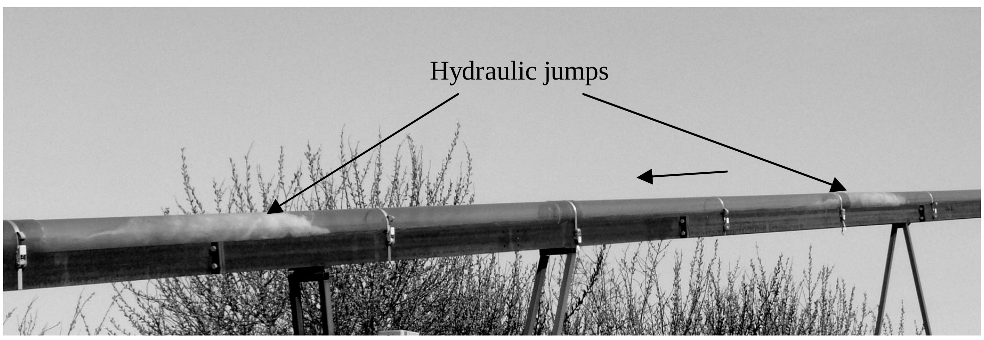

Figure 3: Subsequent hydraulic jumps in facility at the WWTP. Water is flowing from right to left.

The composition of wastewater, i.e. lower surface tension and solids content, does not enhance the air transport in comparison with the air transport in clean water. A new velocity criterion for the occurrence of multiple air pockets in a downward sloping reach has been developed (Figure 4). This criterion defines whether the maximum gas pocket head loss may occur in practice. A new momentum balance for elongated air pockets in downward sloping pipes has been developed [1]. This momentum balance defines the clearing flow number (Figure 4). The new momentum balance is useful in practice to predict the direction and velocity of an elongated air pocket in a downward sloping pipe. The required water velocity to start the transport of an elongated gas pocket to the bottom of a downward sloping pipe reach is $v_{sw} = 0.9 \cdot (gD)^{1/2}$ (or $\mathsf{F}_w = 0.9$) over a wide range of pipe angles (5° – 20°). A physically based predictive model has been developed for the total air discharge by flowing water in downward sloping pipes. The model has been calibrated to a unique dataset of co-current air-water flows [2] (Figure 5). Furthermore, a gas pocket detection method for the prediction of a gas pocket location and total gas volume has been extended and tested in field experiments.

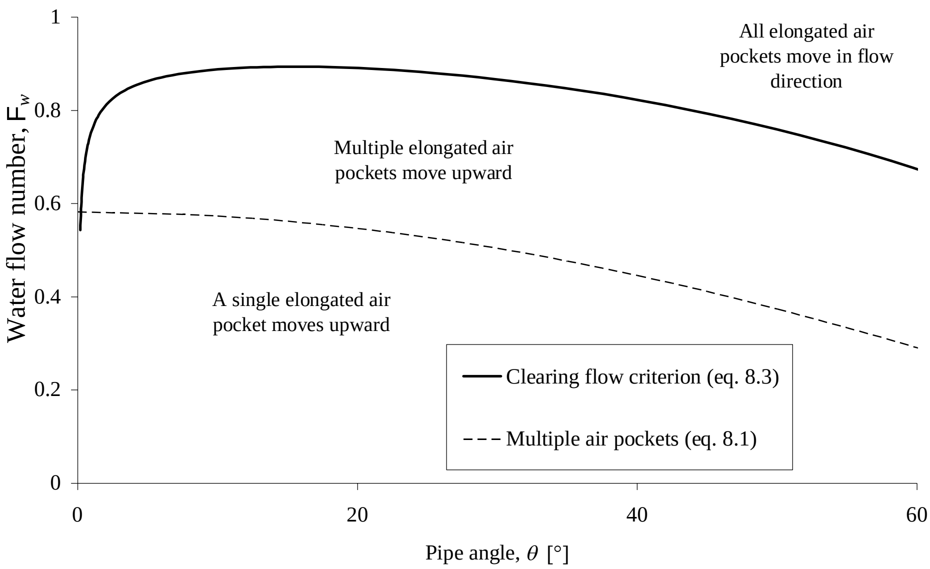

Figure 4: Overview of criteria and elongated air pocket motion in downward sloping pipes

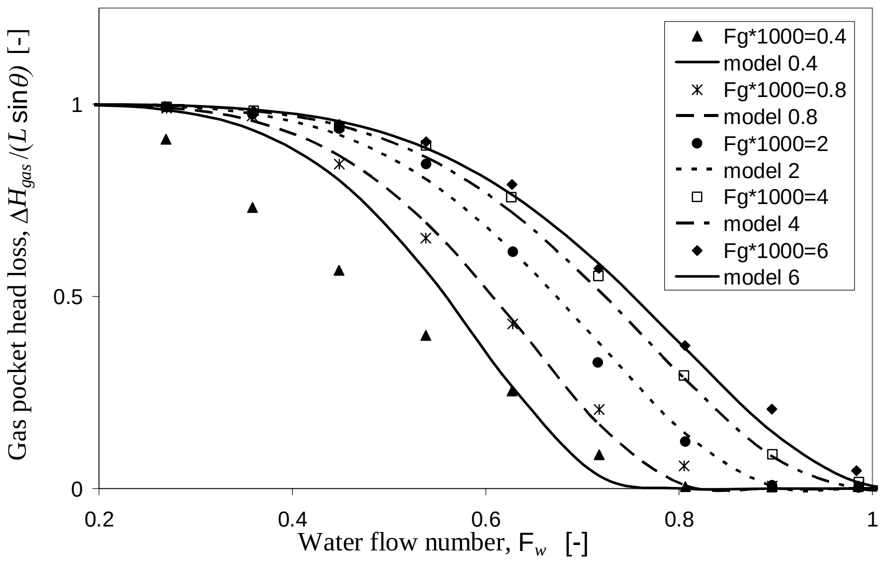

Figure 5: Measured (symbols) and calculated (lines) gas pocket head loss at different combinations of the dimensionless air and water velocity

4. PRACTICAL TRACK

4.1 Approach

The practical track did include a number of activities, including:

1 Experiments to quantify the air entrainment via a plunging jet in a pump pit and mitigating measures,
2 Three meetings per year with all project participants,
3 The development of a Guideline on the hydraulic design and operation of pressurised wastewater mains.

A typical pump pit was constructed in the Deltares Laboratory (Figure 1). The facility had equipment for the accurate measurement of the air discharge into the discharge pipeline, so that the efficiency of different measures to prevent air entrainment could be evaluated. Measures included horizontal deflection plates, vertical deflection plates and aerated T-pieces. Conclusions were integrated into the new Guideline on pressurized wastewater mains [8]; a short summary is provided hereafter.

The progress meetings were combined with workshops or other activities to promote the exchange of knowledge among the project participants. Examples of subjects, that have been addressed in these meetings, include: pipeline pigging and cleaning, history of wastewater pumping stations, pumping station design and operation and monitoring in wastewater collection and transportation systems, to name a few. In this way, these meetings evolved towards a Community of Practice on Pressurised Wastewater Mains; such a Community of Practice had been non-existent in the Netherlands before. The results from the meetings were integrated into the new Guideline on Hydraulic Design and Operation of Pressurized Wastewater Mains.

These new guidelines were drafted by Deltares in close co-operation with an editorial board from the participants. The editorial board included representatives from the pump manufacturer, the water boards and the consultants, so that all available practical experience could be incorporated into the Guidelines [8].

4.2 Results

The air entrainment via plunging jets or after each pump stop may easily exceed the air transport capacity of downward sloping sections [3], because the air transport capacity of downward sloping sections is very small. In order to prevent the accumulation of air, the air discharge should not exceed 0.1% of the water discharge. The air entrainment via the plunging jet is dramatically reduced by the installation of a vertical deflection plate (or aerated T-piece), so that the impingement point of the jet is at sufficient distance of the pump bell mouth. A transient simulation shows which water volume will be extracted from the pump pit by inertia of the pump and the pipeline; this information should be used to determine the required switch-off level to prevent air entrainment. Figure 4 and Figure 5 show that a water velocity of at least $v_w > 0.6{\cdot}(gD)^{1/2}$ (at pipe angles $\theta < 5°$) and $v_w > 0.9{\cdot}(gD)^{1/2}$ (at $5° < \theta < 25°$) is required to prevent significant gas pocket head losses. With a typical design velocity of 1.5 m/s, air pockets may be transported downstream in pipes up to 0.25 m (10″) diameter. Air admission must be prevented at all times in pressurised wastewater mains with D > 0.25 m. The most efficient way to transport air in downward direction by flowing water is through a vertical pipe, because the required water velocity is approximately $v_w \approx 0.4{\cdot}(gD)^{1/2}$. Another recommendation is to prevent negative pressures during normal operations, for example by installing variable speed drives on the pumps and by stopping the pumps at their minimum speed. The following measures may be considered to reduce air in wastewater pipelines (Table 2). All measures are further detailed in the Guidelines [8].

Table 2: Possible mitigating measures to manage air in pipelines

Phase, System part	Measure	Remarks
Design, Pumping station	Add a vertical deflection plate, aerated T-piece or rubber flap to redirection the raw wastewater inflow into the pump pit	This measure is highly recommended if the free falling jet plunges into the pump pit near the pump bell mouth.
	Include a pigging facility, consisting of a Y-piece or by-pass with isolation valves.	Pigging operation could be used for initial filling as well.
	Close air outlet vents in the pumping station	In many pumping stations, these air vents consisted of small ball check valves
	Install instrumentation to monitor the performance of the pumping station and pipeline	Discharge, suction level, discharge pressure, pump speed and power consumption are recommended to compute real-time performance indicators for pumping station and pipeline.
Design, Pipeline	Limit the number of inverted siphons and crossings	HDD length may be at most 1 km
	Limit the depth of an inverted siphon	Depends on geotechnical assessment
	Reduce the diameter of the inverted siphon to increase the the local velocity	Permanent extra energy loss. Foam pig pigging should still be possible, limiting the diameter reduction to 80% of nominal diameter
	Reduce the diameter of the downward sloping section only.	This is only feasible if the HDD can be carried out in upstream direction, so that the larger diameter section is dragged into the drilled hole first.
	Include manual or automatic air vents upstream of inverted siphons	Maintenance required
	Replace a HDD crossing with a traditional crossing, using temporary sheet pilings.	May be cost effective for short crossings in rural areas.
Operation, Pumping station	Raise the pump switch off level	A transient simulation is required to determine the switch off level.
	Improve the pump stop sequence by soft-stopping the pumps.	This limits minimum pressures during normal operations. A transient simulation is required to determine the stop sequence.
	Add a return flow line from the pump discharge back to the pump pit. This line is closed shortly after pump start.	The pipe section between pump and check valve is normally at underpressure during pump stops, so that air and gases come out of solution. The return line releases these gases back into the pump pit.

4.3 Guidelines

The main objective of the Guidelines is to realize a safe, robust, energy-efficient and automatically controlled system for the pressurized transport of wastewater at minimum societal costs. The Guidelines aim to present all aspects and coherence between decisions, made in the design process. Design decisions affect other decision and part of the design process is a cyclic process. The main text is driven by a series of flow charts; see an example in Figure 6. The main text focuses on the required information to support all decisions on the hydraulic design and operation of pressurized wastewater mains. All background information on the physical transport phenomena is collected in appendices. The Guidelines include the following chapters: 1. Preface; 2. Design of wastewater transportation systems; 3. Pipeline design; 4. Pumping station design; 5. Transient events; 6. Review of integrated system; 7. Design considerations to maintain the hydraulic capacity; 8. Commissioning of the system; 9 Monitoring the hydraulic capacity; 10. Literature.

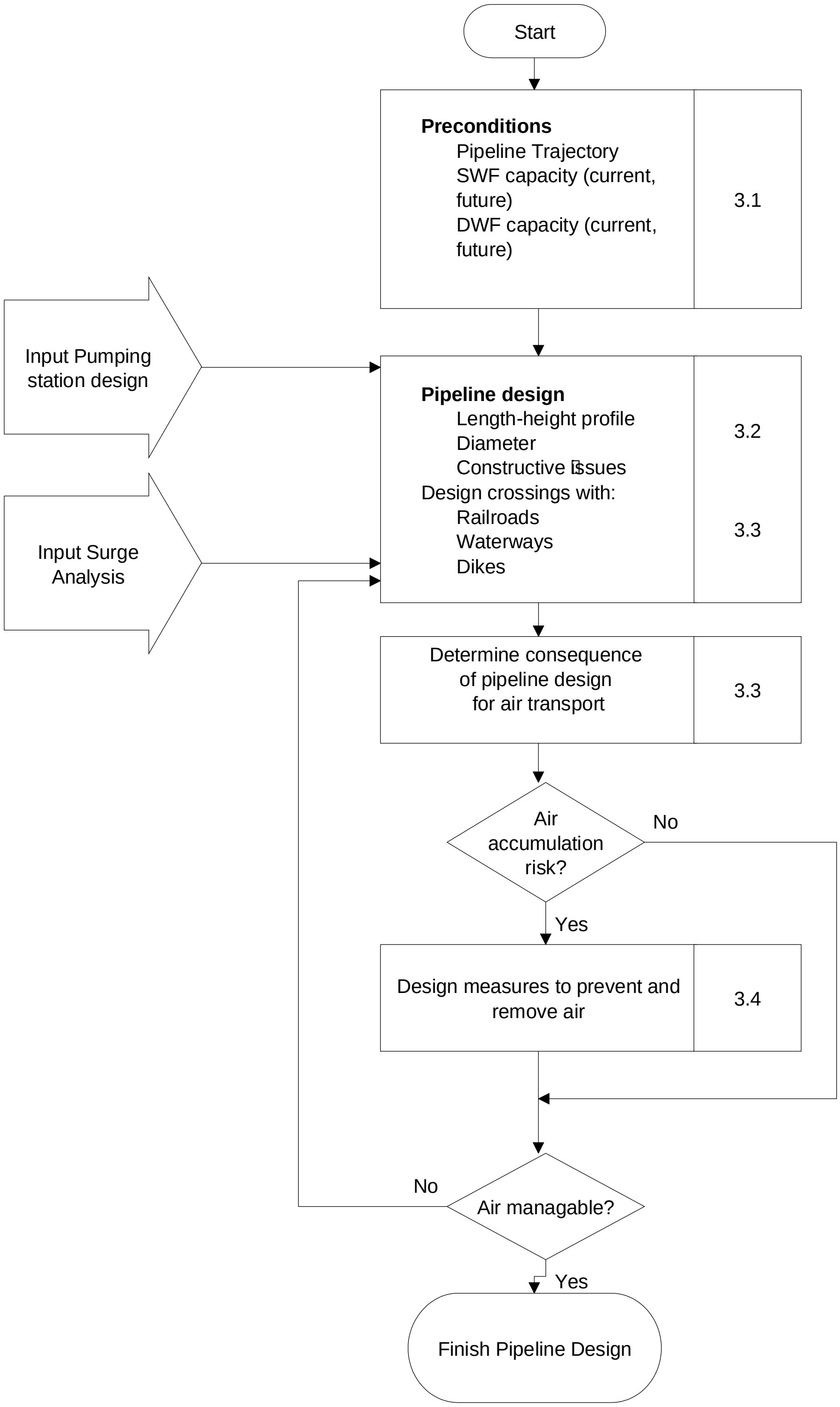

Figure 6: Example of a flow chart from the Guidelines on the chapter Pipeline design.

5. CONCLUSIONS

Seven years of joint industry research has resulted in 2 PhD degrees, 2 MSc degrees, 3 BSc degrees, numerous traineeships, 5 journal papers and more to come, 16 conference papers and numerous popular press articles. The new handbook for hydraulic design and operation of pressurized wastewater mains [8] is being used by most water boards, many municipalities and consultants in the Netherlands. The developed theory is directly applicable to analyze and solve capacity problems due to air accumulations in water pipelines. The proposed model has been applied to pressurized wastewater mains and gravity-driven pipelines [7]. Furthermore, the progress meetings have evolved into a Community of Practice that organizes two or three meetings per year to transfer recent developments and practical experiences. The organization of the Community of Practice is funded by the national foundation for applied research on Urban Drainage and water treatment (STOWA).

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