https://doi.org/10.71573/6ngmws49

Modelling the adoption of combined sewer overflow monitoring technology in Switzerland

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This extended abstract is based on our published work in Water Science & Technology, available at https://doi.org/10.2166/wst.2025.081

Abstract

Combined Sewer Overflows (CSOs) release untreated wastewater during heavy rain, but their impact on water quality and even their magnitude is poorly understood due to limited monitoring. This study develops a prototype of an Agent-Based Model (ABM) to test policies for increasing sensor adoption in CSO monitoring in Switzerland. The ABM simulates the behaviour of key stakeholders, including municipalities, wastewater treatment plant operators, engineers, and cantonal authorities, using the *Theory of Planned Behaviour* and the *Bounded Confidence Model*. It evaluates three strategies: professional events, mandatory sensor installation, and improved sensor technology. Results suggest mandatory installation is the most effective, though findings should be interpreted cautiously due to limited data. The modelling process improved our understanding of the socio-technical system and highlighted the role of social dynamics in technology adoption. Our model integrates multiple knowledge sources, includes a social network structure, and is openly accessible for further development. Key limitations include simplified human behaviour and static assumptions, but ABMs remain valuable to test policies and analyse complex systems.

Highlights

- Agent-based modelling makes it possible to explore policies to improve CSO monitoring in Switzerland, such as mandatory surveillance, professional events, and better sensors.
- In our case study, mandatory CSO monitoring was the most effective approach, but more data is needed to improve the evidence-base.
- Combining multiple knowledge sources in the modelling process provided better insights into CSO monitoring challenges.

How can we convince sewer operators to monitor their combined sewer overflow structures?

Combined sewer overflows (CSOs) release untreated wastewater when rainfall exceeds sewer capacity, contributing pollutants comparable to wastewater treatment plants (WWTPs). While WWTPs have seen major upgrades, improving CSO performance or optimizing wastewater management may offer a cost-effective way to reduce pollution. Despite available monitoring technologies, CSO monitoring remains inconsistent. The updated Urban Wastewater Treatment Directive (UWWTD) now mandates monitoring and reporting, but policy effectiveness varies. In the UK, regulation-driven monitoring expanded rapidly, while Germany's fragmented utility structure led to mixed results, requiring both mandates and bottom-up initiatives. In Switzerland, CSO monitoring is not explicitly required, though some operators voluntarily implement it.

This variability raises key questions about how policies influence CSO monitoring adoption. Agent-Based Models (ABMs) offer a way to explore these socio-technological dynamics, yet their use in policy decisions remains limited. While ABMs have been applied to urban drainage for infrastructure planning, such as virtual sewer networks (Urich and Rauch, 2014) and flood risk management (Zhuo and Han, 2020), their role in technology adoption is underexplored.

This study introduces a novel ABM to examine CSO monitoring adoption in Switzerland, testing policies like regulations and technology improvements. The model integrates the Theory of Planned Behavior (TPB) with an adapted rule catalog (Tillman, 2001) for expert validation and uses the Bounded Confidence Opinion Dynamics (BCOD) model to simulate stakeholder interactions. Our contribution is threefold: (1) analyzing Swiss wastewater stakeholders' roles in CSO monitoring adoption, (2) applying an ABM combining TPB and BCOD to assess policy impacts, and (3) providing an open-access model (Derwort, 2021) for further development, including potential applications in implementing the revised UWWTD.

Defining stakeholders of Swiss wastewater management as agents and modelling their behaviour with the Theory of Planned Behaviour

We used an Agent-Based Model (ABM) to simulate the adoption of sensor technology for monitoring combined sewer overflows (CSOs) in Switzerland. The ABM incorporates the Theory of Planned Behaviour (TPB) (Ajzen, 2002) and the Bounded Confidence Model (BCOD) (Bernardo et al., 2024) to model stakeholder behaviour (Derwort, 2025). The model is designed to evaluate the effectiveness of different policy instruments for promoting sensor adoption. Our methodology involves several key steps:

- **Defining Agents:** The model simplifies real-world stakeholders into four types of agents: municipalities, wastewater treatment plant (WWTP) operators, engineers, and cantonal (sub-state) authorities (Figure 1, top). These agents represent the key decision-makers and influencers in Swiss urban water management. The WWTP operator agent is differentiated from the municipality agent to reflect two different decision-making instances, and two modes of organisation are also considered, where in one, the WWTP operator is responsible for the entire sewer system, and in the other, the municipality is responsible for the sewer system, including the CSOs. The number of agents for each type is based on geodata and expert estimates for Switzerland.
- **Modelling Agent Behaviour with TPB:** The TPB is used to model how agents make decisions about sensor adoption. TPB posits that behaviour is based on intention, which is influenced by attitude towards the behaviour, social norm, and perceived behavioural control (Figure 1, bottom left). In this model, attitude and social norm are merged into a single variable, 'sia' (sensor installation attitude), and a second variable, 'pbc' (perceived behavioural control) is used to represent the agent's perspective on the feasibility of sensor adoption (Figure 1, bottom right). Initial values for these variables are based on available survey data and expert estimates.

- **Modelling Opinion Dynamics with BCOD:** The Bounded Confidence Model (BCOD) is used to simulate how agents exchange opinions on a social network. The model uses the Relative Agreement (RA) algorithm, which assumes that agents influence and are influenced by other agents whose opinions lie within a certain interval. The interactions are scheduled at monthly intervals, reflecting inter-organisational communication. A social network is created based on geospatial data and assumptions about how different agent types communicate.
- **Policy Scenarios:** Three policy scenarios are tested: (1) professional events, simulated by less frequent communication, (2) mandatory sensor installation, simulated by gradually increasing 'sia' when no sensor is adopted, and (3) improved sensor technology, simulated by gradually lowering the 'pbc' threshold. A baseline scenario is also included for comparison.
- **Sensitivity Analysis:** A sensitivity analysis was performed using the Morris method to identify the most influential parameters affecting model outcomes. Numerical experiments were also conducted to assess the model's robustness by modifying communication schedules and network structures.
- **Implementation:** The ABM is implemented in Python, using the Mesa framework for agent-based simulations and is composed of three main modules: data loading, simulation execution, and results visualisation. The code and documentation are openly available.

The primary output of the prototype is the time series of WWTPs and municipalities that adopt sensors over the simulation period (Figure 2, right).

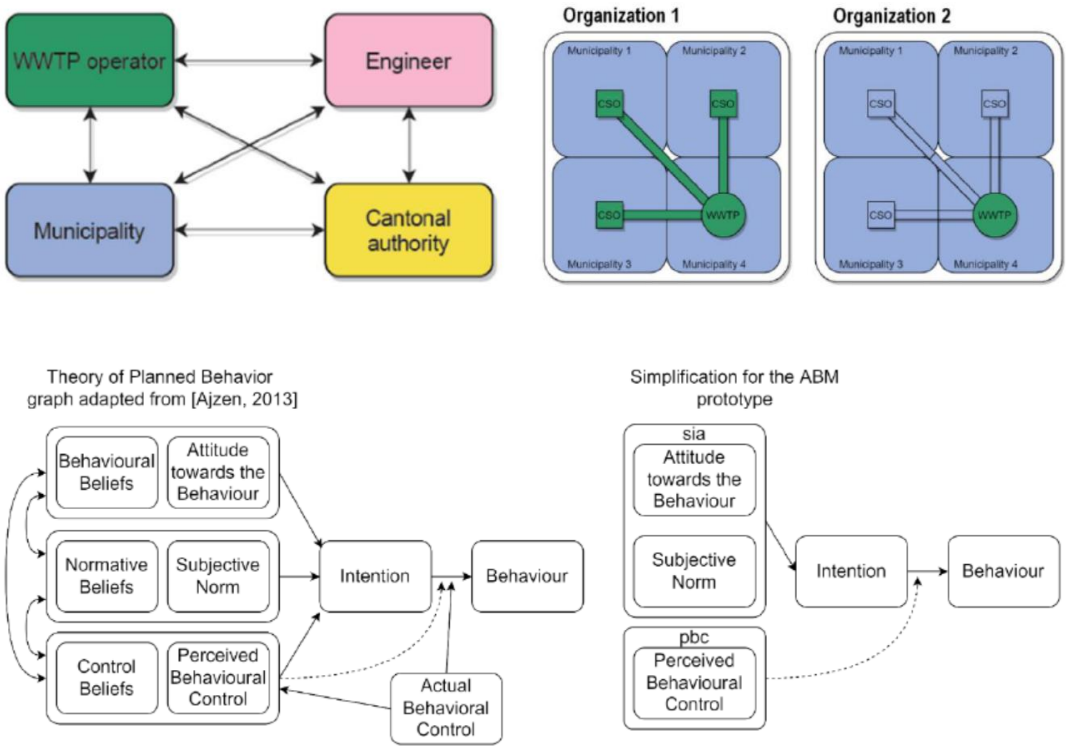

Figure 1, Top: Simplified agents in the ABM (left) and two modes of organizational structure (right) of Swiss urban water management. **Bottom:** Original scheme for TPB adapted from Ajzen (2013) (left) and the simplified framework which was implemented in our study (right). Here, 'attitude' and 'subjective norm' were represented i) by merging attitude and subjective norm into a single variable sia (sensor installation attitude) and ii) by removing the influence of the variable pbc (perceived behavioural control) on the intention.

Results and discussion

Regulation is the most effective policy, nevertheless, adoption is rather slow

The Agent-Based Model (ABM) simulation results show a gradual increase in sensor adoption over time, with municipalities and wastewater treatment plant (WWTP) operators exhibiting different initial adoption levels. In 2017, 21% of municipalities had sensors installed, compared to 67% of WWTP operators (Figure 2, right). Over the 10-year simulation period, these figures increased modestly to 25% for municipalities and 75% for WWTP operators by 2027.

Among the policy scenarios tested, regulation, which is implemented by increasing the sensor installation attitude (sia), appears to be the most effective policy instrument for promoting sensor adoption, doubling the adoption rate for municipalities from 20% to 40% within four years, reaching 60% by the end of the 10 year period (Figure 2, left). In contrast, the impact of the regulation on WWTP operators was minimal, likely due to many already having installed sensors or because they were resistant to adoption due to their initially low sia. Other scenarios, including reduced communication through joint planning meetings and improvements in sensor technology, had smaller effects. The joint planning meetings scenario slightly slowed the adoption rate, while technology improvements led to a slight increase in sensor adoption rates.

The sensitivity analysis showed that the initial parameter settings, especially the initial values of 'sia' among municipalities, have the strongest influence on the model outcome. In contrast, other agents, such as engineers and cantonal authorities, have a limited impact on sensor adoption.

Discussion

The model showed a tendency for sensor adoption to level off over time, differing from expert expectations. This is due to the Relative Agreement Algorithm, which causes opinions to converge. Of all policies tested, only the "Regulation" scenario introduced additional diversity into the system.

Numerical experiments revealed high sensitivity to initial opinion dynamics parameters. The Relative Agreement algorithm simplifies human behavior by assuming static parameters, which are hard to measure and may change over time. The model also excludes external events that could influence opinions.

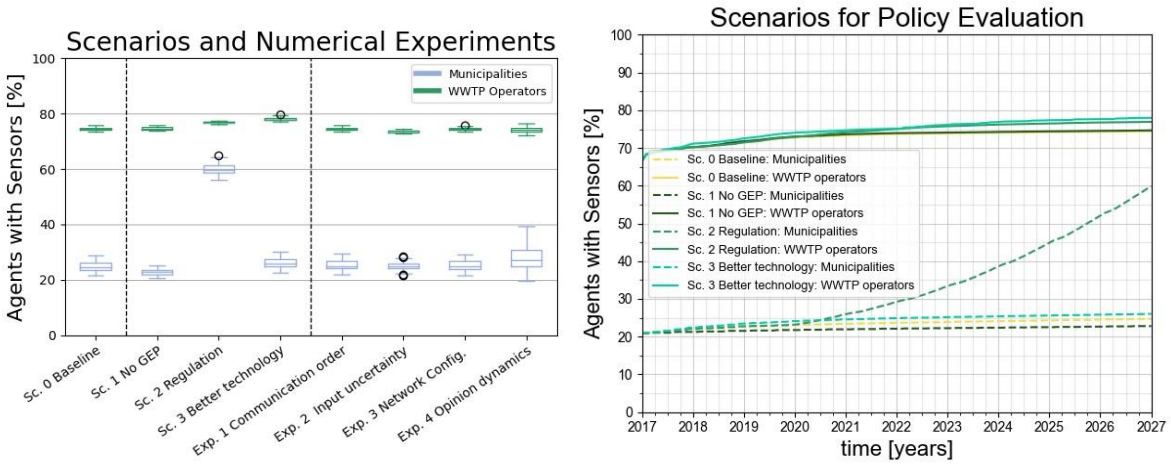

Figure 2: Results of scenarios and numerical experiments for the simulation period from 2017-2027. Left: comparison of scenario/num. exp. results at the end of the simulation period (100 runs each), right: temporal evolution of sensor adoption under different policies (average of 100 runs). A regulation has a big impact and different assumptions for opinion dynamics lead to variability.

The ABM's numerical results should be interpreted cautiously. While the model predicts slow, saturating adoption, real-world trends may differ. Many parameters were chosen ad hoc due to limited empirical data, such as TPB-based survey results. However, developing the ABM facilitated data collection and formalized assumptions for expert validation. The results suggest that authorities and

engineers may overestimate their influence on WWTP operators and municipalities. Additionally, the model does not fully capture the role of sensor adoption in broader digitization strategies. Since policy measures are often combined in practice, ABMs could help identify the most effective policy mix.

Conclusions and future work

In this study we present an Agent-Based Model (ABM) simulating sensor adoption for CSO monitoring in Switzerland. Using the Theory of Planned Behavior (TPB) and the Bounded Confidence Model (BCOD), the results suggest that regulation is the most effective policy, boosting sensor adoption by ~20%, while other scenarios had less than a 10% impact. Based on these findings, we conclude that:

- **Regulation is most impactful:** Mandatory sensor installation is more effective than professional events or technological improvements.
- **Initial attitudes matter most:** The initial 'sia' of municipalities is the strongest influence.
- **Opinion dynamics are complex:** The BCOD-based opinion exchange can lead to opinion convergence over time.
- **Data is needed for validation:** A lack of empirical data makes validation difficult. The future implementation of CSO monitoring in Europe could provide evidence for validation.
- **The involved experts remain cautious about the results** but acknowledge that developing the ABM was valuable. It fosters data collection, integrates diverse perspectives, and enhances understanding of complex systems. Overall, ABMs are a useful approach when the complexity of the system makes traditional methods difficult.

References

Ajzen, I., 2002. Perceived Behavioral Control, Self-Efficacy, Locus of Control, and the Theory of Planned Behavior [1]. J. Appl. Soc. Psychol. 32, 665–683. https://doi.org/10.1111/j.1559-1816.2002.tb00236.x

Bernardo, C., Altafini, C., Proskurnikov, A., Vasca, F., 2024. Bounded confidence opinion dynamics: A survey. Automatica 159, 111302. https://doi.org/10.1016/j.automatica.2023.111302

Derwort, S., Manny, L., Carbajal, J.P., Fischer, M., Rieckermann, J. 2025. Modelling the adoption of combined sewer overflow surveillance in Switzerland. *Water Sci Technol* 1 July 2025; 92 (1): 79–95. doi: https://doi.org/10.2166/wst.2025.081

Derwort, S., 2021. The Impact of Policies for Surface Water Protection During Wet Weather - Prototype of an Agent-Based Model to Assess Non-Technical Challenges to Monitoring CSOs. https://doi.org/10.5281/zenodo.4817330

Tillman, D.E., 2001. Stakeholder analysis in water supply systems (PhD Thesis). ETH Zurich. https://doi.org/10.3929/ETHZ-A-004107705

Urich, C., Rauch, W., 2014. Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. Water Res. 66, 374–389. https://doi.org/10.1016/j.watres.2014.08.020

Zhuo, L., Han, D., 2020. Agent-based modelling and flood risk management: A compendious literature review. J. Hydrol. 591, 125600. https://doi.org/10.1016/j.jhydrol.2020.125600