Sustainable Cities and Society 79 (2022) 103602

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis

Brooke Wilkerson [a,b,*], Eduard Romanenko [a], David N. Barton [c]

[a] System Dynamics Group, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway
[b] Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway
[c] Norwegian Institute for Nature Research (NINA), Gaustadalleen 21, Oslo 0349, Norway

ARTICLE INFO

Keywords:
Stormwater management
Funding strategies
Low impact development
System dynamics

ABSTRACT

Many urban areas around the world are facing increasing pressure on stormwater management systems due to urbanization and extreme weather events caused by climate change. Low impact development (LID), including blue-green infrastructure such as rain gardens, has become an attractive addition to traditional gray infrastructure for managing stormwater.

Municipalities have a limited suite of policy instruments for incentivizing installation of LID on private property. We built a system dynamics model of integrated socio-economic and hydrologic systems in Oslo, Norway to illustrate implementation of two economic incentive mechanisms: subsidies based on reverse auctions and stormwater fees. We find that policy effectiveness depends on 1) communicating realistic expectations of LID performance to landowners and 2) municipal subsidies to reach landowners without intrinsic interests in LID. Under certain conditions, lower municipal economic incentives can outperform higher economic incentives and lead to sustained long-term adoption of LID on private property.

1. Introduction

Stormwater runoff and urban flooding are an increasing threat in built environments around the world. In addition to property damage, extreme precipitation events can cause sewer overflows, which increase sewage treatment costs and threaten water quality (Goonetilleke, Thomas, Ginn, & Gilbert, 2005; Londoño Cadavid & Ando, 2013). Existing traditional (gray) stormwater infrastructure is often aging and under-dimensioned to accommodate predicted increased frequency and intensity of extreme precipitation events as a consequence of climate change (Eckart, McPhee, & Bolisetti, 2017).

Many cities have turned to low impact development (LID) to control volumes and pollutant loads of smaller storm events (Luan et al., 2019). Setting clear policies and expectations for establishing LID in new building projects is relatively straightforward, but in an urban environment, most areas are characterized by a patchwork of small, built properties managed by diverse owners. For example, Oslo, Norway, has implemented a "blue-green factor" regulation for setting minimum requirements for LID in new building projects (Oslo kommune, 2018), but lacks tools for incentivizing adoption of LID on existing built properties. Integrating any new infrastructure – even green infrastructure – into established urban areas can be costly and disruptive (Schifman et al., 2017).

Policies to increase the adoption of LID in established urban areas include raising awareness and economic instruments. Adoption of LID based solely on awareness (advertising) campaigns is quite low. For example, one study in Missouri, USA demonstrated that advertising resulted in less than 10% of households adopting rain gardens (Shin & McCann, 2018). In general, cities must institute more sophisticated combinations of policy instruments to increase likelihood of LID adoption and maintenance.

Two economic instruments explored in the literature and to some extent in practice, include reverse auctions (RA) and stormwater fees (SWF) (Kea, Dymond, & Campbell, 2016; Tasca, Assunção, & Finotti, 2018; Zhao, Fonseca, & Zeerak, 2019). In a reverse auction (also known as a procurement auction), property owners bid to finance part of the cost of establishing LID on their property. The municipality selects owners willing to pay the largest fraction of the cost and establishes the

Abbreviations: LID, Low impact development; SWM, stormwater management; RA, reverse auction; SWF, stormwater fee.

* Correspondence to: Brooke Wilkerson, System Dynamics Group and Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway.
E-mail address: brooke.wilkerson@uib.no (B. Wilkerson).

https://doi.org/10.1016/j.scs.2021.103602
Received 24 September 2021; Received in revised form 9 December 2021; Accepted 9 December 2021
Available online 20 December 2021

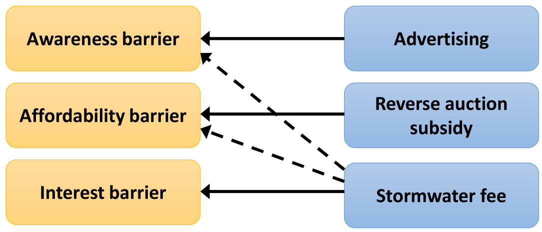

Fig. 1. Relationship between barriers to LID adoption and policies to address those barriers.

LID on their property, with the private landowner sharing the cost of installation (Thurston, Taylor, Shuster, Roy, & Morrison, 2010). In the absence of strict regulations (such as building and development norms), Thurston et al. (2010) argue that an auction is a cost-effective tool for implementing controls on stormwater runoff quantity at the parcel level. Depending on the regulatory setting, a reverse auction may reveal an efficient subsidy mechanism, whereby municipal authorities can determine the minimum subsidy needed to realize a certain amount of LID in a given area.

Stormwater fees are paid by property owners based on indicators of the amount of stormwater the property generates. There is a large variation in the ways stormwater fees are calculated in practice and how closely they are calibrated to the variation in properties' run-off (Tasca et al., 2018). Stormwater fees are utility fees with a similar purpose to solid waste or wastewater. A principle aim of utility fees is to cover direct and indirect costs of management of run-off (Tasca et al., 2018). A secondary effect could be incentivizing landowners to install LID to reduce their stormwater runoff and obtain a discount. We note, however, that the empirical evidence on incentive effects of this kind is limited. While these economic incentives have been implemented in several cities around the world, they are far from widespread and, to our knowledge, there are no cities that have implemented both reverse auctions and stormwater fees (Lieberherr & Green, 2018; Tasca et al., 2018; Zhao et al., 2019). Little is known about how these two policies, which approach adoption of LID from different angles, would function together.

Our research tests implementation of these policies in concert with each other in order to understand policy synergies and tradeoffs and develop strategies for increasing the adoption of LID by private landowners. We particularly focus on knowledge integration in a complex social-ecological-technological system and endogenous dynamics of stakeholder motivation. Literature on policy mix analysis has called for integrated assessment tools to evaluate policy instrument interactions in socio-ecological systems (Ostrom, 2007; Ring & Barton, 2015b).

We built an interdisciplinary system dynamics model that includes hydrologic data, social survey data, results from a reverse auction, and data from spatial/GIS models to test potential impacts of these two policies. As outlined in Abebe et al. (2021) system dynamics modeling has been used in a number of water resources management contexts, including decision support for urban water/wastewater systems management and policies. System dynamics modeling has also been applied successfully to diffusion processes of new technologies (Rahmandad & Sterman, 2008). Our work contributes to this system dynamics literature by modeling diffusion processes for several stormwater management strategies to examine their interactions. The model is demonstrated using data from the Grefsen-Kjelsås neighborhood in Oslo, Norway, and results from the model are aimed at providing generalized insights about policy implementation and generating further discussion about integrated design of policy mixes for stormwater management.

1.1. Low impact development and barriers to implementation

Low impact development (LID) for stormwater includes a suite of approaches to managing stormwater that attempts to incorporate natural features and processes (such as infiltration and evapotranspiration) into stormwater management systems (Eckart et al., 2017). LID can offer many benefits in addition to stormwater management, including filtering polluted water, reducing urban heat island effects, aesthetics, and providing plant and wildlife habitat (Eckart et al., 2017; Elliott et al., 2020; Schifman et al., 2017). Typical examples of LID are small scale, distributed infrastructure such as green roofs, downspout disconnection, and rain gardens. Rain gardens, the focus of our research, are one of the most common LIDs implemented on private property. A rain garden is a man-made depression in the ground that uses plants to infiltrate stormwater and delay peak flows (Dietz, 2007).

As small-scale infrastructure, LID requires widespread adoption in order to have a meaningful impact in stormwater management systems. Infrastructure systems are not only physical and technological. They should be understood as complex, interconnected social, ecological, and technological systems (Markolf et al., 2018). Montalto et al. (2013) have demonstrated that stakeholder engagement and consideration of both physical and social characteristics of an area are key for increasing LID adoption. In this research, through taking an integrated approach, we focus on the economic and social aspects of stormwater infrastructure adoption, with consideration of ecological and technological aspects.

While demographic characteristics such as age and education level can influence adoption (Shin & McCann, 2018), social aspects of LID implementation also include access to information, monetary considerations, personal experiences, and influence from neighbors. On the most basic level, households must first become aware of LIDs before they can form the intention to adopt LIDs (Shin & McCann, 2018). Perceived costs and benefits are associated with LID affect adoption rates (Shaw, 2011). Decision-making is also influenced by knowledge of and experience with flooding. People who are concerned about basement floods are more likely to adopt rain gardens (Shin & McCann, 2018), and people who have experienced basement flooding demonstrate increased willingness to pay to reduce flood frequency (Londoño Cadavid & Ando, 2013). Lastly, studies have found that neighbors' use of a LID practice can positively affect adoption levels (Ando & Freitas, 2011).

For the purposes of conceptualizing these implementation challenges, we identify three key barriers to LID adoption in built up areas:

- *The "awareness barrier"*: LID is a relatively new practice and most of the households are unaware or unfamiliar with it (Cote & Wolfe, 2014; Shin & McCann, 2018).
- *The "affordability barrier"*: LID installation involves a cost, which can be substantial relative to the disposable household income (Cote & Wolfe, 2014; Shaw, 2011).
- *The "interest barrier"*: "Interest" captures the perceived utility (benefits) associated with LIDs. As confirmed by the surveys and reverse auctions conducted in the area, some of the households exhibit intrinsic interest in LID as a stormwater management solution that has potential to mitigate combined sewer overflow (CSO) and household-related floods in the catchment (Furuseth, Seifert-Dähnn, Azhar, & Braskerud, 2018). According to survey results, the primary drivers of "interest" in this area are environmental attitudes and prevention of basement or garden floods. On the other hand, it is reasonable to expect that some households in the catchment may never be interested if they are not impacted by flooding. Even when provided at no monetary cost, LID requires a certain degree of modification to the property, to which a household might not agree if it has opportunity costs or non-monetary inconveniences (Londoño Cadavid & Ando, 2013; Shin & McCann, 2018).

1.2. Strategies for LID implementation

Three policy mechanisms are typically discussed in relation to enhancing LID adoption in existing built-up areas:

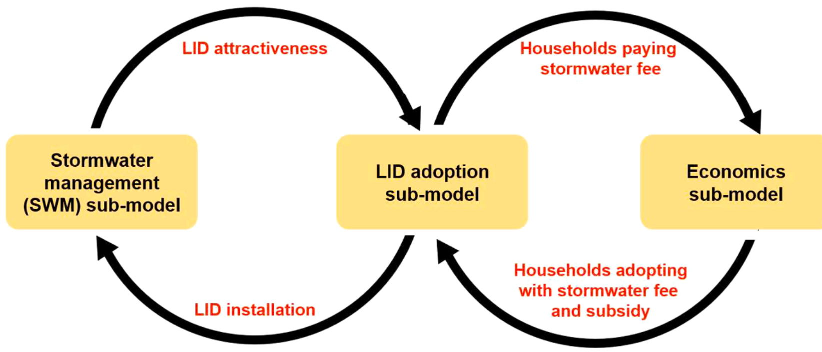

Fig. 2. Conceptual diagram of the sub-models.

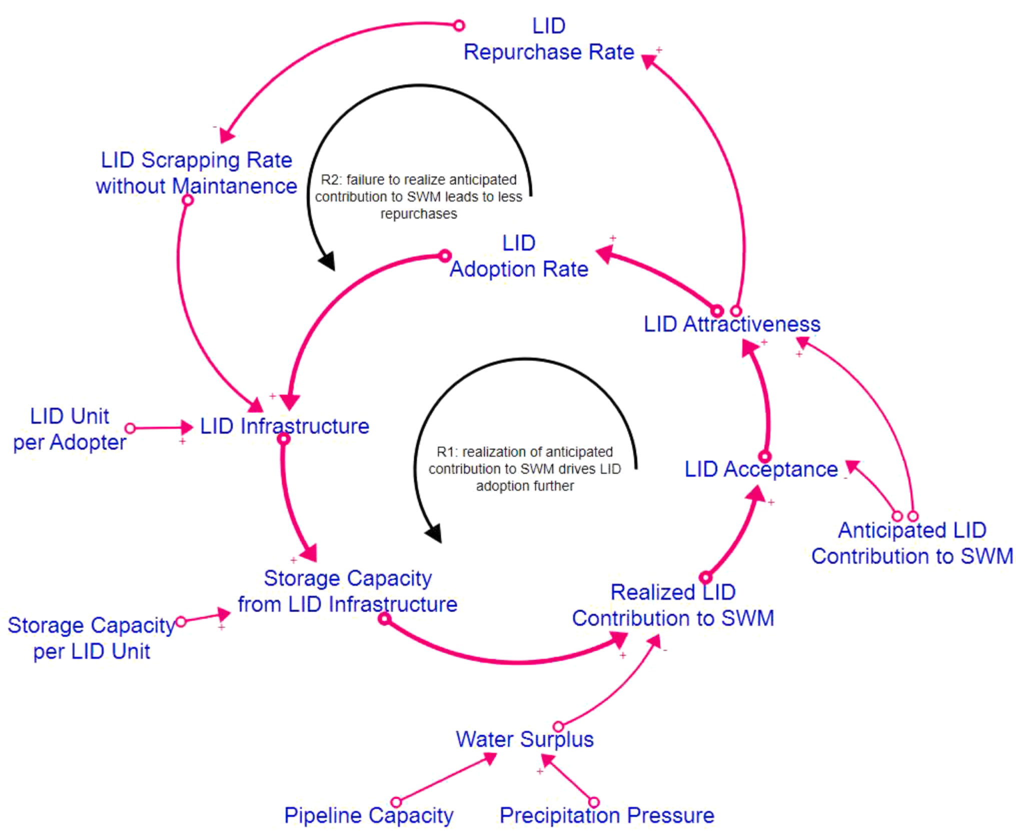

Fig. 3. The dynamic hypothesis for the model.

- *advertisement (awareness raising) campaigns* that disseminate knowledge about LIDs, their value and utilization,
- a *subsidy* that fully or partially covers the cost of LID (as revealed by the reverse auction),
- *stormwater fee* which is paid by homeowners according to how much stormwater runoff their property produces

The first two policies can be easily matched with the first two adoption barriers: advertising campaigns address the "awareness barrier" and LID subsidies address the "affordability barrier" (fig 1). Through increasing awareness, the advertising campaigns are able to effect adoption in households that are previously unaware of LID but do not face affordability or interest barriers. The adoption behavior of these households is captured in typical adoption rates reported as the results of advertisement campaigns (Shin & McCann, 2018).

The rest of the aware and interested households face the "affordability barrier" and need to be provided with a subsidy to become an adopter of LID. It should be expected that a fraction of the households in the catchment who are not interested will not install LID even if its cost is fully covered by a subsidy. Subsidies are typically paired with advertisement campaigns.

The third policy - *Stormwater Fee* - relates to all three barriers by:

- creating awareness about LID as an alternative to paying the stormwater fee ("awareness barrier");
- introducing a monetary benefit of not paying the stormwater fee – an avoided cost - and, thus, addresses the "affordability barrier" for households with intrinsic interest; and
- potentially motivating households without an intrinsic interest in LID as a stormwater management solution by avoiding costs from a waved stormwater fee ("interest barrier").

Fig. 4. Map of the study area in Oslo, Norway. Adapted from (Li et al., 2020).

2. Methods

Exploration of the adoption and implementation of LID in a residential area requires an integrated approach that places the households' behavior in the context of an urban stormwater management (SWM) system. To achieve this, hydrological, socio-economic, technical, and governance sub-systems are closely interconnected and continuously exposed to both internal (policies) and external (climate) pressures in a system dynamics model.

System dynamics models are used to understand complex problems and test policy measures to address those problems, with a focus on feedback mechanisms (loops), delays and non-linear dynamic interactions between a system's components (Forrester, 1970). The model consists of a system of coupled, nonlinear, first-order differential (or integral) equations (Richardson, 1991). Our work contributes to system dynamics literature by looking at diffusion processes for several stormwater management strategies to examine their interactions. It also contributes to the stormwater management literature by exploring policy interactions and their implications among commonly discussed policies for LID implementation on private property.

2.1. The system dynamics model

The system dynamics model integrates hydrological and socio-economic sub-systems, with "slow" (yearly) dynamics (comparable with investments into stormwater management infrastructure), parametrized to the outputs of "fast" (second/minutes) runoff dynamics in hydrological models of the catchment area. The model incorporates the results of a reverse auction-based subsidy implemented in the catchment area and explores the intrinsic value that the residents of a built-up area might place on LID. The model also explores potential trade-offs, unintended effects and synergetic effects of LID policies. The model is flexible enough to simulate a variety of assumptions about the adoption potential for LIDs, thereby reflecting the high degree of uncertainty inherent in policy instrument interactions. Understanding the dynamic relationships between potential adopters, adopters, and nonadopters has been shown to be critical to understanding LID implementation (Shin & McCann, 2018).

The model is an explorative tool that generates scenarios and examines how households in an urban residential area could respond to LID implementation policies (de Gooyert, 2019). The scenario analysis of the model generates generalized insights on the LID diffusion trajectories in both the near-term and the longer-term. Data sources for our model include hydrological models (Li et al., 2020), distribution of household willingness-to-pay for rain gardens determined through a reverse auction applied by (Furuseth et al., 2018), survey data (Furuseth et al., 2018), studies of economic costs and benefits of LID implementation (Lekkerkerk, 2020), and spatial models of existing green space and infiltration capacity (Sælthun, Barton, & Venter, 2021). These data sources were supplemented with interviews with subject matter experts from water management and planning authorities (see parameter tables in Appendix A).

The model consists of 12 stocks and 172 variables, and a full model description is available in Appendix A. The model consists of three interconnected sectors: Stormwater Management (SWM), LID Adoption, and Economics (fig 2).

The SWM sub-model captures three important aspects of the system. It (1) tracks LID infrastructure installed on the properties of households-adopters, (2) captures the realized contribution of installed LID infrastructure to SWM goals in the catchment, and (3) links that contribution to LID attractiveness, which impacts the decision of households to become adopters or discontinue being adopters. The SWM sub-model is instrumental to operationalizing the feedback loops in fig 3. The LID Adoption sub-model contains the adoption structure that develops the adoption potential indicated by *LID Attractiveness* from the SWM sector. This sub-model is based on the diffusion of innovation paradigm (implemented as a modified Bass diffusion model), which is a common framework for modeling adoption and diffusion of innovation (Horvat, Fogliano, & Luning, 2020). We note that we use the term "attractiveness" to mean "appealing" or "desirable" in line with this paradigm. The Economics sub-model is where the SWF and RA policies, which affect LID adoption, are modeled.

The central premise of the system dynamics model is that in a residential area where some households are impacted by the consequences of stormwater runoff, including CSO and property floods, at least a fraction of these households is expected to derive benefit from LID as a stormwater management solution (fig 3). This premise is captured by the concept of *LID Attractiveness*, formulated in terms of a fraction of the households in the catchment who are interested in installing LID. *LID Attractiveness* essentially represents the baseline adoption potential for LIDs in a context with no existing stormwater management regulations or incentives.

The policy mechanisms we explore in our scenarios are aimed at realizing the potential indicated by *LID Attractiveness*. However, the potential itself is likely to be dynamic. Initially, the households rely on anticipated performance of LIDs to store excess stormwater during rain events, which is communicated via advertising campaigns. As more interested households become adopters, more LID infrastructure is installed in the catchment area and more experience is gained about the actual contribution of LIDs to stormwater management.

Over time, the households compare the advertised contribution of LIDs with the actual contribution, which can sustain or reduce the public acceptance of LIDs as a SWM solution. If the anticipated contribution of LID is met, public acceptance is sustained, which will stimulate further realization of LID adoption potential (illustrated as loop R1 in fig 3). On the other hand, if LID performance is less than anticipated, the acceptance of LID will be reduced. This would reduce LID attractiveness among households and lower adoption rates despite incentive policies. Since LIDs have a limited lifetime and need to be reinstalled, lower LID attractiveness will necessarily reduce reinstallation. Reductions in both first-time installation from adoption rates and reinstallation from existing adopters will decrease the number of LIDs in the catchment, which will lead to even lower LID contribution to SWM, lower acceptance and attractiveness and the risk of serious resistance to incentive policies (loop R2 in fig 3). The described feedback mechanisms are represented by two reinforcing feedback loops in fig 3 and form the dynamic hypothesis of the study.

The model does not explain or determine the adoption potential, but rather assumes the adoption fraction that a decision-maker (municipality) perceives to be desirable and realistic and explores the deviation of an actual adoption process from this target/fraction. The realization of the adoption potential is driven by the endogenous adoption structure of the model, which is affected by RA and SWF policies and performance of stormwater management in relation to LID adoption dynamics. Based on interviews with experts working with LID in Oslo, we assume the municipality has a target adoption fraction of 20% in our scenarios.

2.2. Study area

The city of Oslo, the capital of Norway, has ambitious plans for stormwater management in new building projects (Oslo kommune, 2013), but existing built-up areas, with no plans for transformation or development, do not fall under the stormwater regulatory requirements. Performance-based green area indicators are being introduced in parts of Norway, while economic incentives have to date not been tried in as part of the LID policy mix (Oslo kommune, 2019).

The Grefsen-Kjelsås neighborhood has a catchment area of 1,44 km^2 and consists primarily of detached and private houses with large green gardens and few residential blocks (fig 4). Buildings, streets and pavements cover an estimated impermeable surface of 22%. The sewer system in Grefsen-Kjelsås is 60% combined and is designed with a Combined Sewer Overflow (CSO) acting as a relief valve by allowing untreated wastewater discharge into the receiving river Akerselva.

A CSO event is normally expected to occur once every three years. However, under current precipitation conditions and the constrained sewer system, a CSO event occurs several times per year, including during relatively small rainfall events. The pollution resulting from CSOs affects water quality, habitats, and riparian and coastal recreation opportunities. In addition to CSOs, some properties in the catchment experience garden and basement floods during intense rainfall events. Similar to CSOs, the frequency of the property floods is considered to be higher than normal. The reduction of CSOs is recognized by municipality of Oslo as the main stormwater problem in Grefsen-Kjelsås, and LIDs, which complement the existing sewer system, are considered among the central solutions to addressing this problem (Furuseth et al., 2018).

Grefsen-Kjelsås is representative of many urban residential areas, where neighborhoods of single family homes have densified over time, and sewer systems are at times overwhelmed by precipitation events. Notably, public spaces in the area are small and diffuse, and can therefore only make a limited contribution to stormwater management. As the dominant land use, privately owned residential properties offer the greatest opportunity for implementing LID in the area.

2.3. Model parameters

With the aim of highlighting key household adoption dynamics, we made the following simplifying assumptions:

- Only rain gardens are considered as an available LID solution. Rain gardens are a common form of LID installed on private property, and relative to other types of LID, there is more data available about installation and maintenance costs and infrastructure lifetime (estimated to be 30 years; see Appendix A, section A.1 for more detail). Using a single type of LID allows for a focused analysis of adoption dynamics.
- Reference (fixed) values of stormwater fee, LID cost and LID subsidies are used in the model, and the model incorporates the effects of distribution of households around these reference values.
- The number of households in the catchment is kept constant. Only households with green space (identified by GIS mapping, see Appendix A) are counted as eligible households for rain gardens in the model.
- "Grey infrastructure" (e.g. drainage network, impermeable built surfaces) is kept constant.

Given the assumptions of a constant number of households and constant capacity of gray infrastructure, the system dynamics model is intended to be simulated for 30 years (2020-2050). A full list of parameters is included in Appendix A, model documentation. The parameters, initial values and climate scenarios of the model are calibrated to the case of Grefsen-Kjelsås (Appendix A). However, the structural mechanisms are assumed to be generic to a built urban area.

2.4. Description of scenarios

The model is used to generate scenarios that provide insights on the dynamics of realizing LID adoption potential under the two policy

Table 1
[redacted]

Scenario set	Scenario number	RA Subsidy	Dimensioning assumption (year return period)	SWF (NOK)
Advertising and subsidy scenarios	1	–	5	–
	2A	25%	5	–
	2B	90%	5	–
	2C	90%	20	–
Stormwater fee scenarios	3A	–	5	400
	3B	–	5	800
	3C	–	20	800
Combined policies scenarios	4A	90%	5	800
	4B	25%	5	800
	4C	67%	5	800

instruments. While reporting the scenario results, the variables of interest are the adopters of LID as a fraction of total households (*Realized Adoption Fraction*) and the water storage capacity associated with the stock of installed LID infrastructure relative to water surplus (run-off) in the catchment area (*LID Contribution to SWM*). The first variable captures the extent of LID diffusion, which is typically referred to in the literature as adoption rate or implementation rate, and the second variable reflects the contribution of the installed LID infrastructure to SWM capacity.

The following variables are used (Table 1):

- *Dimensioning assumption*: captures the role of LID as a SWM solution in terms of LID's SWM capacity for rains with 5-year or 20-year return periods. 5-year rain is the default dimensioning. Dimensioning to 20-year rain represents the context in which heavier rain events may exceed LID capacity to manage stormwater.
- *RA subsidy*: reverse auction determined subsidy formulated as a fraction of LID cost; reflects the degree of cost-sharing between the households and the municipality.

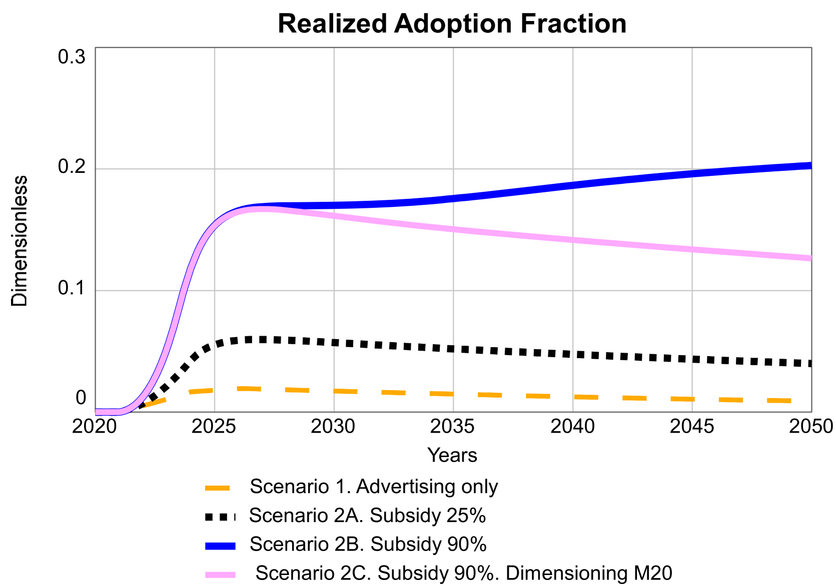

Fig. 5. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

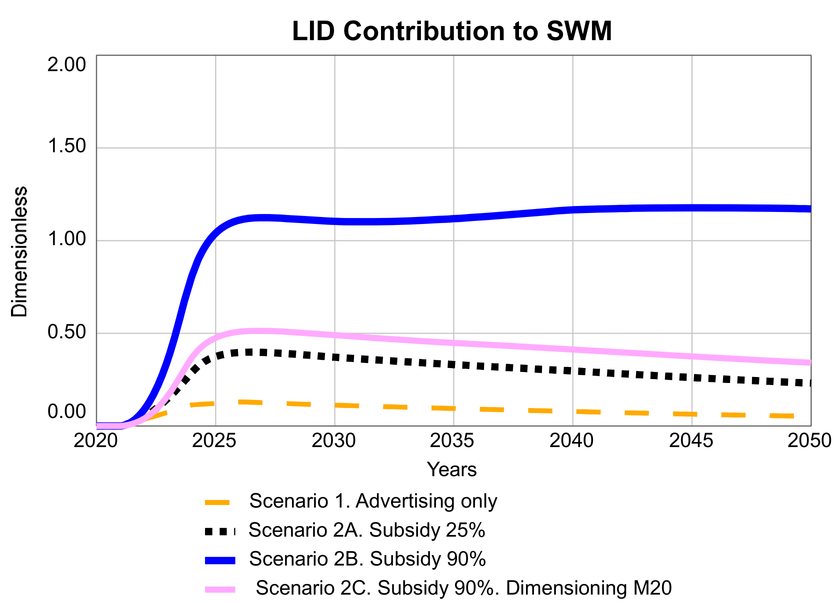

Fig. 6. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

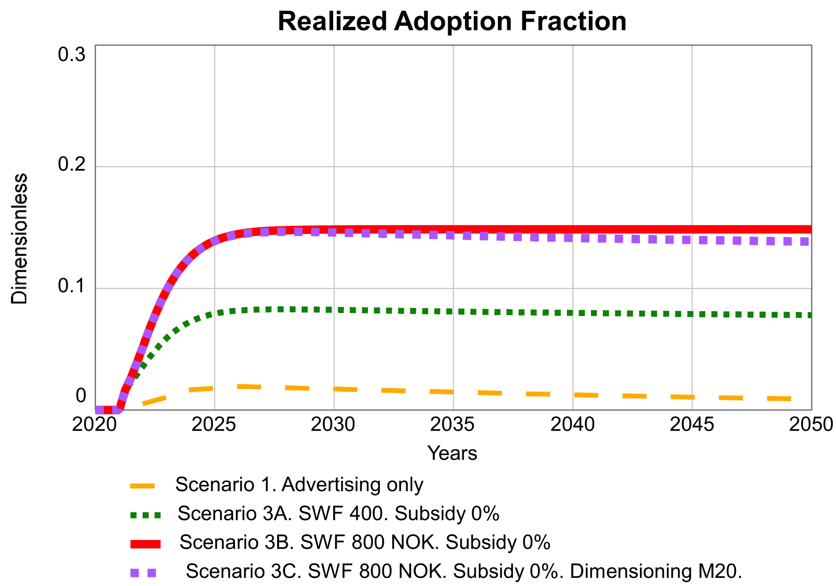

Fig. 7. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

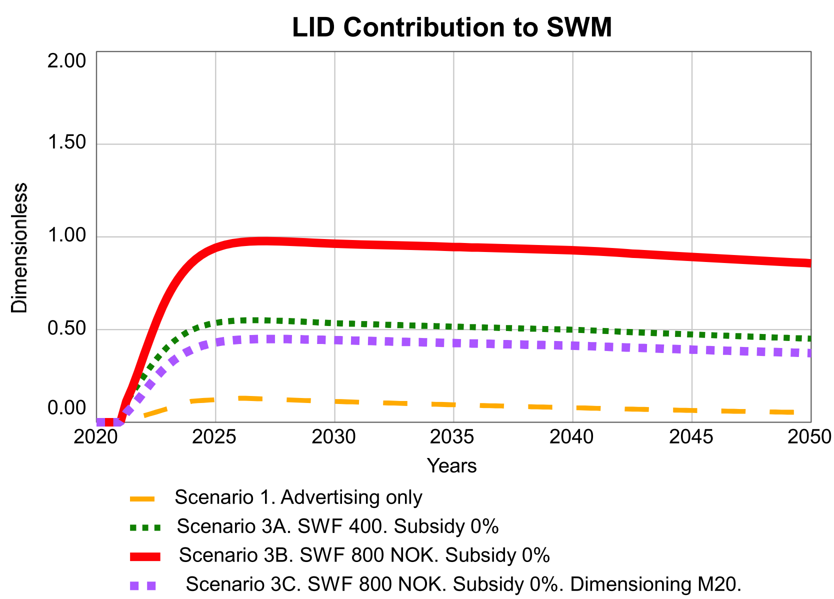

Fig. 8. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

- *SWF (NOK)*: expresses the stormwater fee in Norwegian kroner (NOK) per household per year. At the time of model construction, 1 NOK was equivalent to 0.10 EUR (DNB, 2021).

3. Results

We present results as three sets of scenarios (Table 1). The first set of scenarios explores the advertising and subsidy policies as well as how people's expectations of LID shape adoption trajectories. The second set of scenarios explores the effect of the stormwater fee on LID adoption. The third set explores how subsidies and stormwater fees could function in concert to optimize LID adoption.

3.1. Advertising and subsidy scenarios

Scenario 1 represents a situation with only an advertising campaign (running from 2021 to 2024) to raise awareness. The awareness campaign on its own is able to create a small increase in adoption while it's active, but within a few years of its conclusion, the LID adoption fraction begins to decline (fig 5). This is because the policy attracts relatively few adopters in the absence of other incentives, and, over time, a fraction of these adopters do not re-adopt LID as their LID ages.

Scenarios 2A and 2B demonstrate the result of an advertising campaign plus a reverse auction-based subsidy. As participation in the reverse auction is voluntary, households need to be made aware of the policy (through advertising) in order to participate. These scenarios present a publicly funded LID diffusion strategy that uses a minimum of willingness-to-pay by the households with intrinsic interest in LIDs and assumes that there is no limit to the municipality's budget for subsidizing LID. This is in contrast to the combined policy scenarios presented in section 3.3, in which revenue from the stormwater fee is the financing mechanism for the reverse auction-based subsidy.

Scenario 2A introduces the reverse auction-based subsidy at a modest level of 25% (households pay 75% of the cost of installing LID).

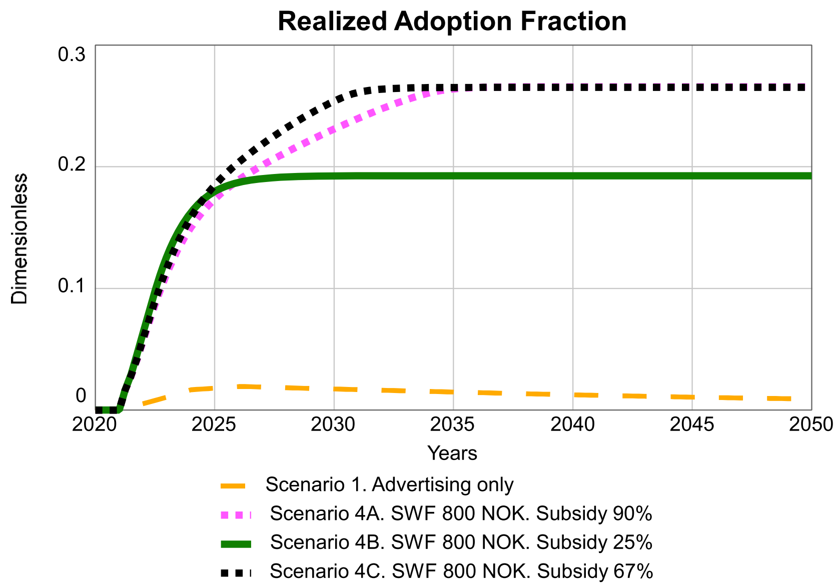

Fig. 9. Realized adoption fraction. We assume the municipality has a goal of 20% (0.2) adoption.

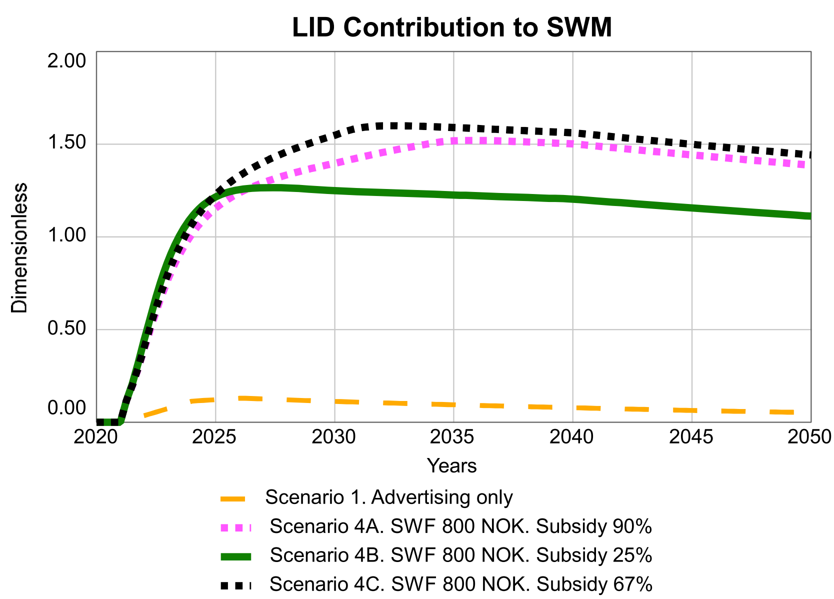

Fig. 10. LID contribution to stormwater management, where a value of 1 on the Y-axis indicates 100% of desired storage capacity from LIDs.

In this scenario, the *Realized Adoption Fraction* increases initially, but peaks at about 6.0% (fig 6). As with Scenario 1, low LID adoption fractions contribute to low perceived effectiveness of LID and low re-adoption of LID, resulting in a gradual decline in the adoption fraction for the rest of the simulation.

In *Scenario 2B*, a generous 90% subsidy policy results in sharp increases in the *Realized Adoption Fraction* within the first 6 years to about 16.7%. The adoption fraction keeps growing gradually over the rest of the scenario to slightly over 20%, which marginally exceeds the adoption target (fig 5). The high adoption fraction results in LID storing 100% excess water, which corresponds to the maximum *contribution to SWM* (fig 6). The gradual increase in adoption fraction comes from the effect of the reinforcing feedback loops. Since the adoption happens fast enough to increase the storage capacity from LID beyond the expected storage, LID attractiveness continues to increase beyond 20%. Consequently, some of the initially non-attracted households develop interest in LIDs and a fraction of them are motivated to become adopters by the subsidy.

This scenario demonstrates that high subsidies together with an effective advertising campaign that clearly communicates realistic expectations for LID as a stormwater management solution within the likely climate scenario leads to timely realization of full LID adoption potential. In addition to the anticipated contribution of LID to SWM being realized, the actual performance of LID exceeds the expectations and leads to a slight positive increase in initial adoption potential. *Scenario 2B* is an ideal diffusion scenario, which, however, comes at a high public costs associated with 90% subsidies. Unsubsidized rain gardens are estimated to cost 10,000 NOK/m2 to install (Furuseth et al., 2018). In our model, an unsubsidized 7 m2 rain garden is calculated to have an annualized cost (installation and maintenance) of 3,560 NOK.

Scenario 2C demonstrates the role of dimensioning assumptions and the importance of the design of advertising campaigns. The scenario takes *Scenario 2B* as a starting point but assumes rains with 20-year return period. These heavier rains will at times exceed the capacity of

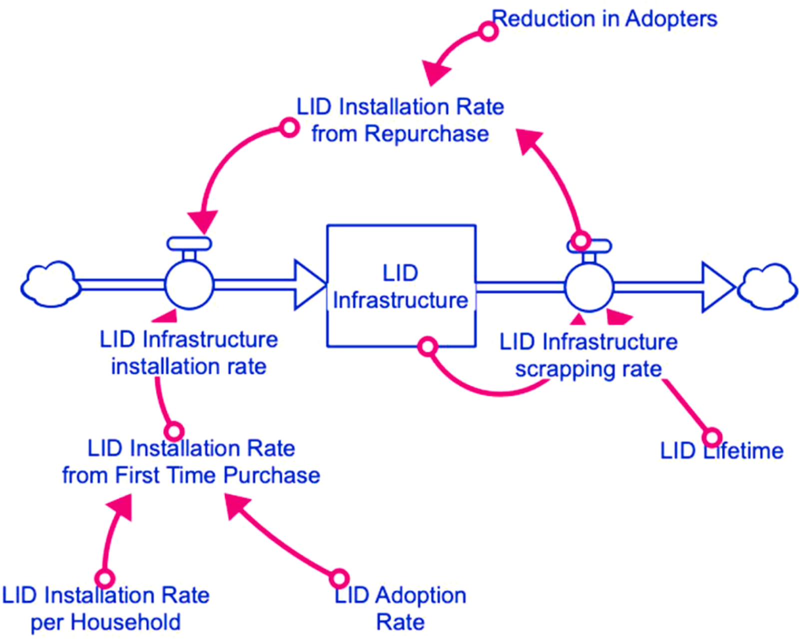

Fig. A1. Simplified stock and flow structure of LID infrastructure.

Table A1
List of important parameters for SWM sub-model

Parameter	Value	Unit	Reference
LID Lifetime	30	Year	Expert elicitation, literature review
LID Installation Rate per Household	1	LID Unit/ Household	Reflects the Oslo municipality's expectation that only one LID unit is likely to be installed by a household
Time to Change LID Attractiveness	1	Year	Model calibration
Time to Perceive Realized LID Contribution to SWM	7	Year	Model calibration
Time to Change LID Acceptance	15	Year	Model calibration
Reference LID Coverage	20	Square Meters/ LID Unit	(Kukadia, Lundholm, & Russell, 2018)
Reference Storage Capacity per LID	3.8	Cubic Meters/ LID Unit	(Kukadia et al., 2018)
LID Coverage	7	Square Meters/ LID Unit	(Furuseth et al., 2018)
MIN LID Attractiveness	0.03 (3%)	Dimensionless	Approximation of lowest reported adoption rates for rain gardens in (Shin & McCann, 2018).

LID. As a result, households form an impression that LIDs are not effective at managing stormwater. As households perceive low LID effectiveness in relation to larger rain events, the adoption fraction gradually declines. *Scenario 2C* demonstrates a considerable sensitivity to the dimensioning assumption and points to the importance of designing an advertising campaign that clearly communicates the limits of LID, in addition to the benefits.

3.2. Stormwater fee scenarios

These scenarios explore implementation of a stormwater fee without a LID subsidy. The stormwater fee promotes LID adoption among households who want to avoid the fee. For these households, avoiding the stormwater fee adds to the perceived benefit of LID in a benefit/cost ratio.

Scenario 3A presents a SWF of 400 NOK/year. The fee promotes rapid adoption of LID among the households that are sensitive to that fee level. After initial growth, the adoption fraction remains stable over time at about 8%, far below the goal of 20% adoption (fig 7). The stability can be explained by the fact that households are motivated primarily by the fee instead of LID performance or intrinsic interest. As a consequence, the LID contribution to stormwater management is only about 50% of the desired level (fig 8), which indicates that the SWF needs to be higher to realize the desired level of LID.

Scenario 3B (*SWF of 800 NOK*) tests the LID diffusion strategy that is based on a stormwater fee of 800 NOK. In this case, the realized adoption fraction is only slightly lower than in *Scenario 2B (Subsidy at 90%, with no SWF)*. While the realized adoption fraction is lower than the desired 20%, the LID contribution to SWM remains at or near 100%. This result indicates that the impact of the stormwater fee alone on LID diffusion can be comparable to the effect of 90% RA subsidies.

Scenario 3C simulates a SWF of 800 NOK but with the dimensioning assumption of 20 years. As with scenario 2C, this represents a case in which households develop falsely high expectations of LID performance under rain events with a 20 year return period. While these overly high expectations caused a drop in adoption over time in scenario 2C, in scenario 3C, they have little effect on long term results. This is because the stormwater fee is held at a constant level regardless of the actual performance of LIDs, making householders relatively insensitive to LID performance. This scenario illustrates the power of the extrinsic motivation created by the stormwater fee.

3.3. Combined policies scenarios

This set of scenarios demonstrates the effect of implementing the stormwater fee (SWF), which is set to a reference value of 800 NOK/household/year, together with the reverse auction-based subsidy. In contrast to the first set of scenarios, LID subsidies are constrained by the availability of funds in the stormwater fee account. Income from the stormwater fee accumulates in the stormwater fee account and is earmarked for LID subsidies. *Scenario 4A* portrays the reference adoption trajectory with the stormwater fee and generous subsidies (*Subsidy Fraction* at 90% of LID Cost). *Scenarios 4B and 4C* explore moderate and low subsidies.

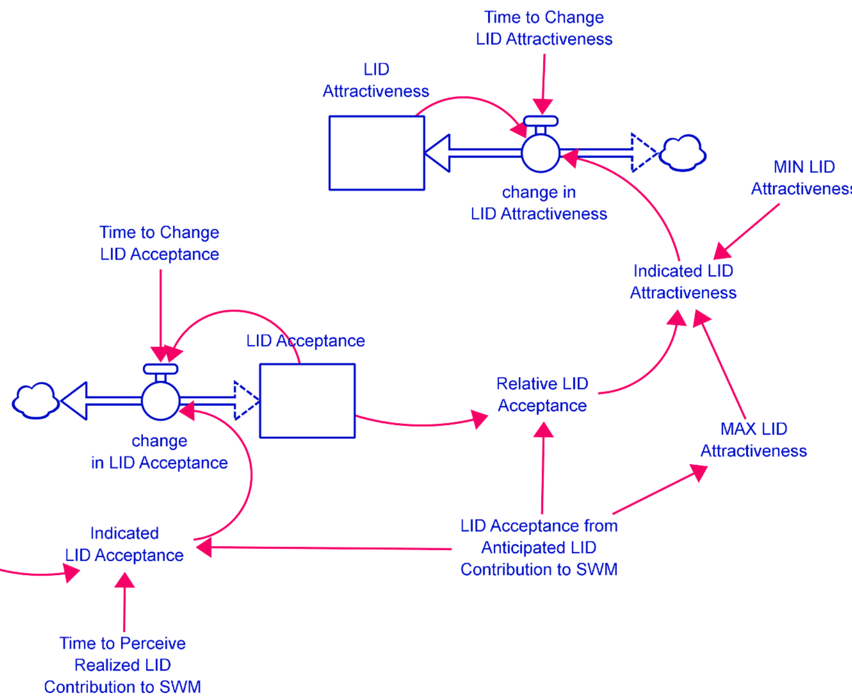

Fig. A2. Stock and flow structure of LID acceptance and LID Attractiveness.

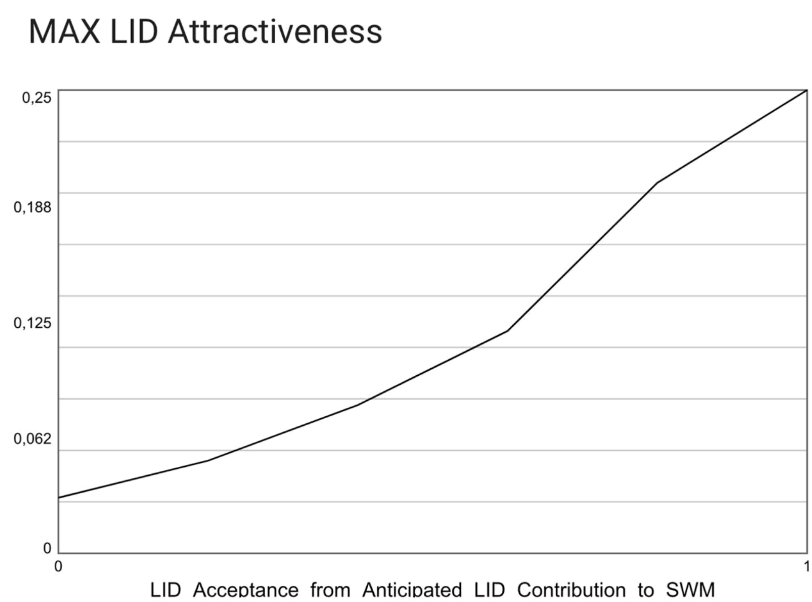

Fig. A3. Table function for Max LID Attractiveness.

For *Scenario 4A*, the adoption trajectory during the first 4 years is steep (fig 9). After year 2025, the adoption growth continues at lower yet quite moderate rates. The ultimate adoption fraction stabilizes around year 2035 and exceeds the adoption fraction achieved in *Scenario 2B* (26.6% and 20.3% respectively). LID contribution to SWM develops in a similar fashion to the adoption fraction (fig 10). Higher adoption fraction results in very high storage capacity from LIDs providing 152% of required storage capacity in 2035. This surplus in stormwater management capacity becomes useful later when precipitation pressure grows. Even though climate change (and resulting increased precipitation) causes a decline in LID contribution to SWM, the achieved adoption fraction remains stable.

Scenario 4B and 4C experiment with different subsidy fractions. Since the reverse auction-based LID subsidies are financed by the stormwater fee income, lower subsidy fractions indicate a higher degree of cost-sharing and affect the rate at which the funds of the stormwater fee account are utilized. In other words, lower subsidy fractions mean that more households can receive subsidies. The scenarios explore the dynamic trade-off between lower subsidies which attract a lower number of adopters, and higher subsidies which attract more adopters but drain the RA budget more quickly.

Scenario 4B tests the effect of low RA subsidies, with a representative subsidy fraction of 25%. At this level of subsidies, close to 19% adoption fraction is achieved within the first 5 years, which is higher than in *Scenario 2B*. The adoption trajectory exhibits very slight decline through the rest of the scenario due to lower LID contribution to SWM which is now affected by climate change. However, in 2050, the adoption fractions are only slightly lower than in *Scenario 2B* (19.3% and 20.3%

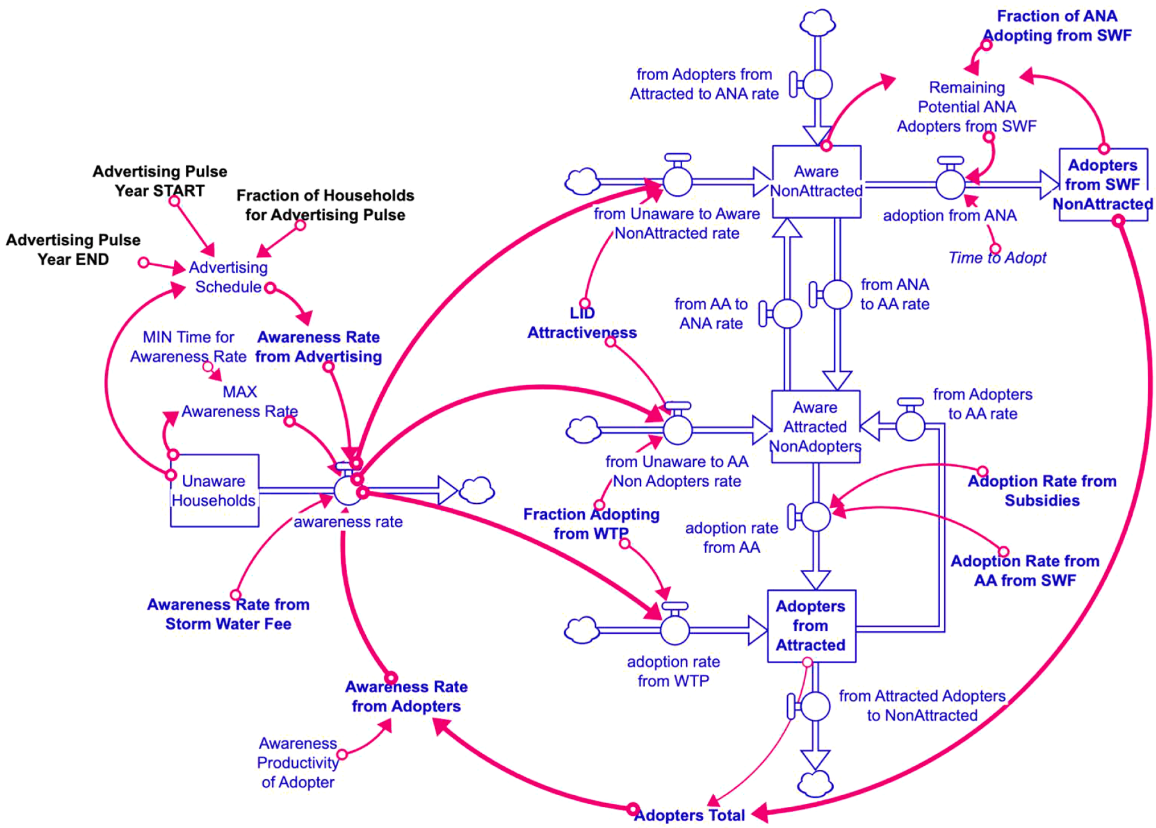

Fig. A4. Simplified stock and flow diagram of LID adoption structure.

Table A2
List of important parameters for LID adoption sub-model

Parameter	Value	Unit	Reference
MIN Time for Awareness Rate	0,25	Year	Reflects the assumption that it will take a year for all the households to become aware about LIDs
Time to Adopt	1	Year	Reflects the assumption that around 63% of attracted households will install LID within a year at full subsidy
Time to Become Attracted	1	Year	Set to be symmetrical to Time to Adopt
Total Households	873	Household	According to the GIS analysis for the catchment area, reported in (Lekkerkerk, 2020)

respectively). *Scenario 4B* indicates that there can be significant potential for cost-sharing when the stormwater management regulation such as the stormwater fee is a part of the LID diffusion strategy.

Scenario 4C reveals probably the most interesting insight. From a dynamic perspective, moderate subsidies (such as 67% subsidies) can improve the adoption projections relative to *Scenario 4A* (generous subsidy). As fig 9 shows, there is a faster and steeper adoption between years 2025 and 2030 at moderate subsidies. This is due to the dynamics of funds availability and the trade-off between the subsidy fraction and the amount of subsidies that could be supported financially. At moderate subsidy fractions, more subsidies can be allocated to more households from the stormwater fee fund, which effectively speeds up the diffusion process. The additional economic motivation that the stormwater fee provides for attracted households compensates for the loss of adopters from lower RA subsidies. Though the revenue from the stormwater fee is reduced over time (as more households adopt LID), the adoption fraction remains stable as LID is perceived as effective.

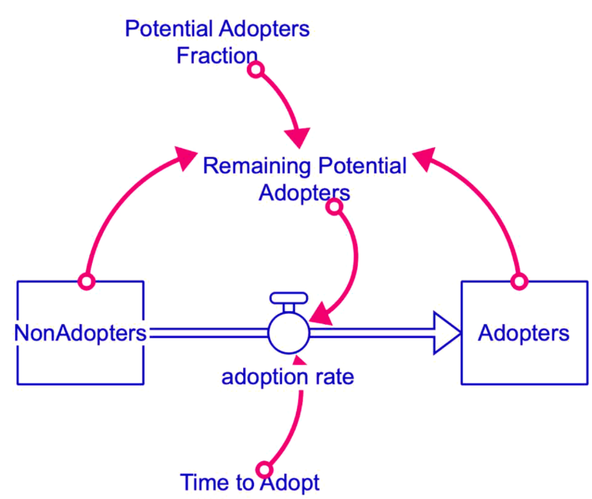

Fig. A5. Generic structure of remaining adoption potential.

4. Discussion and conclusion

Our quantitative system dynamics model integrates quantitative and qualitative data to improve understanding of LID implementation in built up areas under different policy scenarios. We focus on the adoption process within an interlinked socio-economic and hydrologic system.

4.1. Findings and policy implications

Our modeling results suggest that a simple advertising/awareness campaign is insufficient on its own to stimulate widespread adoption of LID. Low levels of LID adoption can add to a perception of LID having

Table A3
List of important parameters for policy effects sub-model

Parameter	Value	Unit	Reference
LID Cost per Coverage	10,000	NOK/Square Meter	(Furuseth et al., 2018)
Fraction of LID Cost for Willingness to Pay	0.1	Dimensionless	Consistent with the average bid for rain gardens during the reverse auction conducted in 2018 as in (Furuseth et al., 2018)
Interest Rate	0.0175	Dimensionless/Year	Approximates 10-year real interest for 10-year government bonds; calculated from (Norges Bank, 2020)
Time to Perceive Costs and Benefits	1	Year	Consistent with adjustment time in LID Adoption Sub-Model
Elasticity of Adoption to Benefit to Cost Ratio for Attracted	1	Dimensionless	Assumes unit-elasticity
Elasticity of Adoption to SWF for NonAttracted	1	Dimensionless	Assumes unit-elasticity
LID Coverage/area	7	Square Meters/LID Unit	(Furuseth et al., 2018)

limited effectiveness and further erode adoption over time. Though awareness campaigns may have limited effectiveness on their own, they are a key component of the reverse auction-based subsidy policy.

A reverse auction-based subsidy can be an effective policy (relative to a general stormwater fee) for increasing LID adoption rates because it is targeted at a specific LID measure, though high subsidies may be needed to ensure continued stable adoption and re-adoption over time. In our scenarios, subsidies of 90% were needed to reach the target adoption fraction of 20%. Further, our scenarios illustrate how households can be sensitive to LID effectiveness. When faced with 20 year rain events, LID effectiveness is reduced, which in turn reduces the attractiveness and adoption fraction of LID. This demonstrates the importance of clearly communicating realistic expectations for LID capacity and functionality in advertising campaigns.

Obtaining reductions in the stormwater fee can also serve as an effective source of motivation for LID installation, increasing adoption fractions and reaching households both with and without intrinsic interest in LIDs. Because stormwater fees are calculated on total runoff (from all surfaces, not just rain gardens), the incentive effect on LID adoption relative to a targeted payment via auction is low. Furthermore, the adoption trajectories under the stormwater fee are less sensitive to the dynamics of LID attractiveness driven by dimensioning assumptions because the fee is not tied to the effectiveness of LID under different intensities of rainfall events. This implies that the uncertainty about adoption potential and advertising the role of LID as a stormwater management solution is less critical if the stormwater fee is a part of the policy mix. We note, however, that implementing a stormwater fee may be politically difficult, as it depends on estimating the storm runoff from individual properties. In the case of Oslo, a proposal for a stormwater fee adopts a two stage approach which allows private property owners to challenge municipal calculations if land cover is inaccurate or LID measures have been implemented that have not been identified. The property owner returns a corrected description of the property and a recalculation of the stormwater fee using an online app (Barton, Venter, Sælthun, Furuseth, & Seifert-Dähnn, 2021).

A combination of the reverse auction-based subsidy and stormwater fee policies allows for a fee collected across all property owners to be reallocated to a much smaller number of cost-efficient properties, such that implementation of the stormwater fee can support implementation and expansion of LID measures, with targeted use of the subsidy. In fact, the scenarios reveal that using stormwater fee revenues to finance moderate reverse auction-based subsidies can facilitate faster adoption in the near-term without necessarily reducing the adoption potential in the long-term. Lower subsidy fractions mean that more households can receive subsidies.

Much of the existing literature on urban stormwater policies considers instruments individually, be they stormwater fees (Abebe et al., 2021; Tasca et al., 2018; Zhao et al., 2019) or reverse auction-based subsidies (Thurston et al., 2010). Tasca et al. (2018) discuss how stormwater fees operate at the interface between water management, emergency management, pollution control, and land-use management, effectively requiring a policy mix for implementation. Zhao et al. (2019) discuss the evidence that stormwater utility credits or discounts implemented with stormwater utility fees provide greater flexibility to adopting best management practices and reduce stormwater runoff at a lower overall cost to the community. To our knowledge, the present

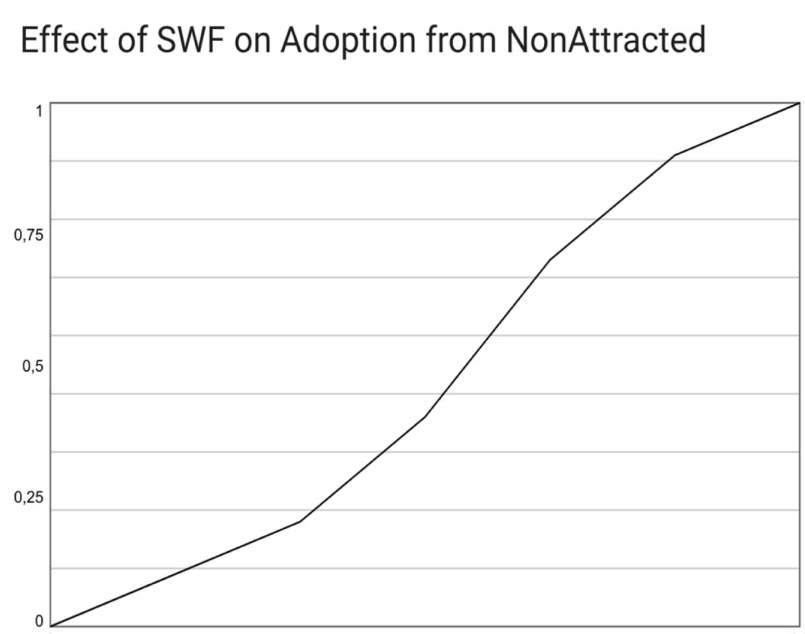

Fig. A6. Table function for Effect of SWT on Adoption from Non-Attracted

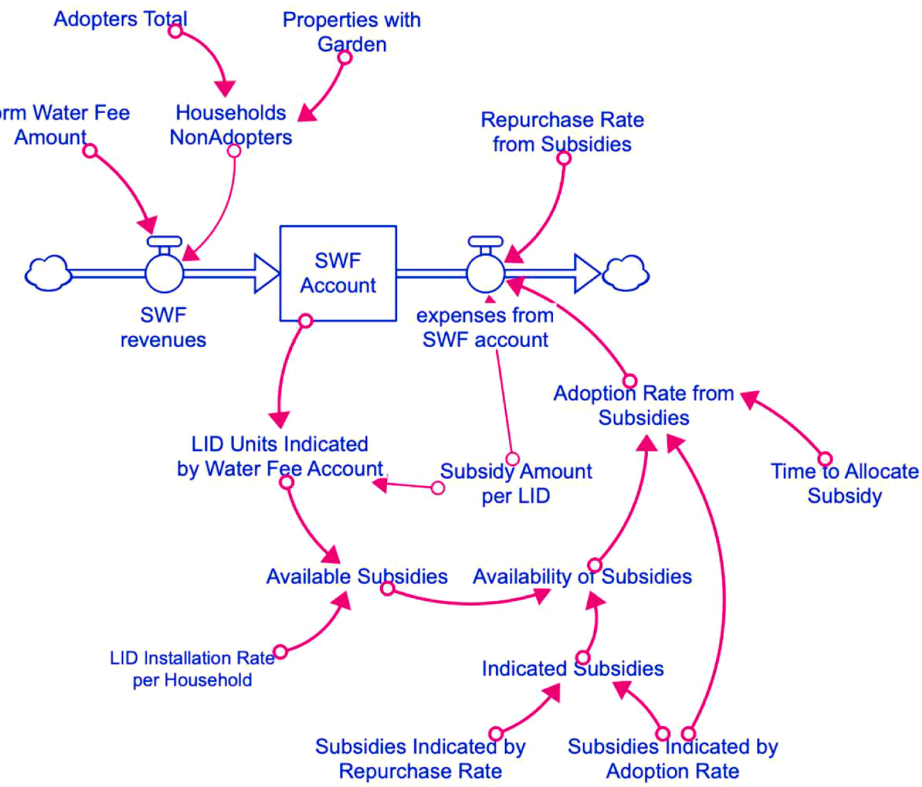

Fig. A7. Simplified stock and flow diagram of SF account sub-model

study is the first to explicitly model the interactions of stormwater fees and subsidies for LID implementation.

While system dynamics models have been built to analyze combined policy instruments in other domains (for example, Gerber, 2017), the specificity of policy instruments and environmental issues makes it difficult to draw comparisons across domains.

4.2. Limitations and future work

As a tool for investigating potential behavior patterns and how they could change over time, the model illustrates how households could react to LID implementation policies and perceived LID effectiveness. The scenarios demonstrate the model's capability to generate a wide array of LID adoption trajectories, given the assumptions about the adoption potential, the municipality's strategy to realizing this potential, and a portfolio of policies to support such strategy.

Further development of the model could include adding additional types of LID (such as green roofs or permeable pavement) and a more dynamic representation of gray infrastructure. Including population dynamics and socio-economic forces, such as housing prices, could capture larger societal impacts (including environmental justice issues) of an LID-based stormwater management strategy (Hoover, Meerow, Grabowski, & McPhearson, 2021). A better understanding of households' perceptions, experiences, and capabilities would help explain motivation and adoption, and research into "motivational crowding" in relation to LID implementation could provide a more nuanced picture of household motivation in relation to fees and subsidies (e.g., Ezzine-de-Blas, Corbera, & Lapeyre, 2019; Ureta, Motallebi, Scaroni, Lovelace, & Ureta, 2021;(Akers and Yasué, 2019)). Though the model includes LID maintenance costs, we see value in further exploration of monitoring and maintenance issues, including the perceived burden and liability of LID maintenance for private landowners that could affect adoption (Dhakal & Chevalier, 2017). Lastly, studies of reverse auction, subsidy and stormwater fee implementation and adoption rates (either alone or in concert) in other municipalities could help validate parameters in this model and strengthen model insights.

This work could also be further developed by extending the model with explicit links to regulatory frameworks and their understanding of stormwater. For example, in current Norwegian practice, municipalities are only allowed to charge water and sewer fees that are directly related to providing those services. Though they can change over time, regulatory frameworks create structures that must be navigated when considering when and how stormwater policies can be implemented. A policy mix perspective that considers multiple information, regulatory and economic instruments can help identify synergies and tradeoffs among institutional frameworks (Barton, Ring, & Rusch, 2017; Barton et al., 2017; Ring & Barton, 2015a, 2015b).

Further, a stormwater fee is based on a legal argument that the private property owner is responsible for external costs related to stormwater management that have been shifted to the municipal utility (akin to a "polluter pays" principle). A reverse auction-based subsidy does not explicitly rest on this argument and instead tries to allocate limited funds effectively to interested property owners, who voluntarily enter an agreement with the funder. These two approaches have therefore a fundamentally different understanding of a property owner's legal responsibilities to manage storm runoff from their property. In addition, under current regulations governing pricing of municipal utilities in our case study area, fees can only recover a utility's costs of service provision (Barton et al., 2021). Currently, regulation does not allow a stormwater fee to fund an LID subsidy to customers, even if the subsidy is aimed at reducing the utility's stormwater costs. In summary, implementation of a reverse auction-based subsidy and stormwater fee in concert may challenge existing regulatory frameworks and expose tensions in how stormwater is understood and defined in the urban context. These tensions may reduce the desirability of directly linking these policies.

This study contributes to the existing LID literature by considering LID implementation in a built-up area in the context of an urban stormwater system, where hydrological, socio-economic, and governance sub-systems are closely interconnected. The use of system dynamics methodology to develop a dynamic model allows formalizing both "hard" quantitative and "soft" qualitative aspects of LID adoption and stormwater management. The scenario analysis has been performed for the specific area of Grefsen-Kjelsås in Oslo. However, the structures developed for the system dynamics model are representative of a generic built-up area and, therefore, the model can be calibrated to other catchments, given the availability of data.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

Acknowledgement

This work was supported by the Norwegian research council through the project New Water Ways (270742). We wish to thank Isabel Seifert-Dahnn, Hong Li, Ingvild Skumlien Furuseth, Bent C. Braskerud, and Line Johanne Barkved for helpful comments and feedback.

Appendix A: Full model documentation

This model is built in Stella Architect. Model documentation is presented by sub-model, with visual excerpts of the model to aid understanding. In sum, the model consists of model consists of 12 stocks and 172 variables. Parameter values are listed in a table at the end of each sub-model description. Values for key parameters that are not taken from literature or expert interviews are determined by partial- and full-model calibration against available data for the study area.

A.1. Stormwater Management (SWM) Sub-Model

LID Infrastructure is tracked by a stock variable that accumulates the difference between installation rate and scraping rate (fig A.1). **Installation Rate** combines installations from first-time purchases and from repurchases. **Scrapping Rate** is formulated as a first-order exponential decay over specified **LID Lifetime (**Table A1).

Installations from first-time purchases are driven by **LID Adoption Rate** in **LID Adoption Sub-Model**. The parameter **LID Installation Rate per Household** converts adoption rate, which is formulated in terms of households, into LID installation rate, which is formulated in terms of LID units, and is set to value 1 to reflect the municipality's expectation that only one LID unit is likely to be installed by a household. Since the LID installation per household assumption is portrayed explicitly as a parameter, it can easily be changed by a model user. **LID Adoption Rate** combines adoption rates from all the three categories of potential adopters in the model: those attracted to LID and who do not need an incentive, those attracted to LID and who need an incentive and those whose interest in LID comes from SWM regulation (the stormwater fee).

LID Installation Rate from Repurchase is determined by LID scrapping rate and the adopters who decide to continue using LID. Current adopters decide not to repurchase LID if the conditions that impacted their previous purchase decisions have changed: LID became less attractive, an incentive decreased, or the SWM regulation became weaker (the stormwater fee amount decreased). The model tracks these changes and recalculates realized repurchase rates accordingly. Repurchases from subsidies are tracked separately since they are subject to budget constraints in a limited subsidy case.

LID Attractiveness is driven by acceptance of LID as a viable SWM solution among the households (fig A.2). LID Attractiveness adjusts towards the indicated value exponentially over **Time to Change LID Attractiveness. LID Acceptance** captures the propensity of the residents to participate in SWM by installing LID at their property. Note that, according to this conceptualization, even 100% subsidy requires acceptance of a household to install LID. A financial incentive that covers the full cost of LID is assumed to be sufficient to realize the full adoption potential indicated by LID Acceptance, whereas a financial incentive that covers the cost of LID partially is assumed to realize only a fraction of this potential.

LID Attractiveness is formulated in terms of **adoption potential**, that is, a fraction of all the households in the area that would install LID at 100% subsidy. It is unlikely that all the households will install LID even when a financial incentive that covers the full cost of LID is provided. On the other hand, the experience of LID adoption in other countries (Shin & McCann, 2018) and the results of the survey in Grefsen-Kjelsås (Furuseth et al., 2018) indicate that some residents install LID even without any financial incentive. Therefore, the model specifies minimum and maximum LID Attractiveness. **MIN LID Attractiveness** is taken from values presented in (Shin & McCann, 2018). **MAX LID Attractiveness** indicates the maximum adoption potential from a financial incentive (and, therefore, does not include adoption potential from SWM regulation) and is influenced by anticipated role of LID in SWM.

LID Acceptance is formulated in terms of **LID Contribution to SWM**, a variable that captures the interaction of LID Infrastructure with the hydrological system of the catchment. This contribution is defined as storage capacity from all installed LIDs combined relative to water surplus in the catchment. **Storage Capacity** associated with LID infrastructure within the catchment is calculated from the stock of LID Infrastructure assuming average **Storage Capacity per LID Unit**. The unit-level storage capacity is proportional to average coverage of LID unit assumed for the catchment, given the relationship between storage capacity and coverage of a reference LID unit. **Water surplus** is excess runoff that accumulates during intense rain events and leads to combined sewer overflow (CSO). In principle, besides CSO, the access runoff has another undesirable consequence in the catchment: household-related floods, namely garden and basement floods. Household-related floods and the potential role that LID can play in reducing their extent justify the municipality's expectation of intrinsic value that some of the households might place on LIDs. However, since the available information about household-related floods is anecdotal and these floods are typically correlated with CSO events, for which more quantified evidence has been gathered by (Furuseth et al., 2018), water surplus associated with CSO is chosen to be the only reference for assessing LID contribution to SWM.

Essentially, **LID Acceptance** captures the effect of LID performance over time on **LID Attractiveness**. The dynamics of this effect is such that, when exposed to advertisement, households receive information about expected LID performance and form perception of anticipated LID contribution to SWM. As LIDs are being installed and sufficient utilization time elapses, households update their perception of LID performance. As a result, the **LID Acceptance** gradually evolves from initially formed perception of anticipated LID contribution to SWM to the perception of realized LID contribution to SWM. The potential for the described dynamics of **LID Acceptance** is inherent in the structure portrayed in Fig. A.2.

Two time constants characterize the speed of LID acceptance dynamics: **Time to Perceive Realized LID Contribution to SWM** (set to 7 years to allow for sufficient observations of rain events with 5-year return period) and **Time to Change LID Acceptance. Time to Change LID Acceptance** is set to 15 years, a half of LID lifetime. This reflects the consideration that it may take some years to experience stronger floods; households may need to experience more than one flood to understand the impact of LIDs; and households need time to adjust their beliefs/perceptions of the value of LID even after the impact/benefit of LID is clear.

A higher anticipated contribution of LID to SWM indicates a higher value for **MAX LID Attractiveness**. This relationship is portrayed by the table function (Fig. A.3) that reflects the estimated responsiveness of adoption potential to expected LID performance that is communicated to the residents during advertisement campaigns. Such relationship is necessarily an expert estimation that incorporates a number of informed assumptions, both quantitative and qualitative. The use of a table function is a convenient way to operationalize such expert estimation. Note that the model does not determine the adoption potential, but uses a decision-maker's (municipality) aim for a realistic adoption potential and simulates the trajectory of realizing this potential at various policy designs. In this sense, the table function for **MAX LID Attractiveness** is a heuristic that represents the mental model of municipality. The model then assumes that the adoption potential corresponds to this heuristic and explores the deviation of an actual diffusion process from the adoption potential driven by the endogenous adoption structure of the model, which is exposed to the impacts of policies, performance of SWM impacted by LID adoption dynamics and the exogenous pressures of climate scenarios.

LID Attractiveness is a type of variable that is typically referred to as a "soft variable". However, since it is formulated in terms of potential adoption fraction, it can be easily related to LID contribution to excess water storage. The table function assumes that LID contribution beyond the excess water in the catchment (above 100%) does not have an impact on LID attractiveness. On the other hand, the interviews with Oslo municipality stakeholders revealed that 25% adoption fraction is considered to be sufficient in providing the required SWM capacity for 5-year rains. Therefore, the upper bound value for MAX LID Attractiveness is set to 25% and corresponds to 100% LID Contribution to SWM. The values for MAX LID Attractiveness for lower values of LID Contribution to SWM were estimated by simulating the model iteratively in a 90% unlimited subsidy mode (no financial constraints to realizing a given adoption potential) under various climate scenarios (see the discussion on climate scenarios below).

LID Acceptance relative to **LID Acceptance from Anticipated LID Contribution to SWM** indicates how close **LID Attractiveness** at any point in time is to **MAX LID Attractiveness**. When **LID Acceptance** is at anticipated contribution, **LID Attractiveness** takes its maximum value. If **LID Acceptance** goes below anticipated contribution, **LID Attractiveness** is between its minimum and maximum values. **MIN LID Attractiveness** is set to 3% corresponding to the lowest adoption rates observed for LIDs as a result of advertising campaigns (Shin & McCann, 2018).

By definition, the water surplus is the excess runoff relative to existing pipeline capacity in the catchment. Therefore, the variable **Water Surplus** captures precipitation profile typical for the catchment relative to the SWM capacity in place (without LIDs). Eq. A.1 formalizes this conceptualization of water surplus.

$$WaterSurplus = \frac{RunofffromaRainEvent}{PipelineCapacity} \tag{A.1}$$

Rain events vary by intensity and duration, where the intensity is characterized by a return period (3-year rains, 5-year rains, etc.) and duration is measured in time units (mins). The SWM systems are designed (dimensioned) to withstand a rain event with a specified intensity and duration characteristics. A common reference rain event commensurate with CSO problem is 60 min rain with a return period of 5 years. A more robust SWM system can be dimensioned to rain with a return period of 20 years, though LID infrastructure alone is unlikely to provide meaningful contribution to such system.

Hydrological modeling of the catchment provides a water surplus value typical for Grefsen-Kjelsås (Li et al., 2020). Due to long lifetimes, the pipeline capacity, which is the denominator of **Water Surplus**, can be assumed fixed over the model's time horizon. However, since the precipitation profile is expected to be impacted by climate change, the numerator of **Water Surplus** is both not constant and uncertain. The anticipated effect of climate change on precipitation is captured by climate factors that effectively increase the dimensioning requirements for SWM systems. In the context of Eq. A.1, an appropriate reference rain event for 2050 might be the one with higher intensity and/or duration than in 2020. The hydrological modeling incorporated climate factors in their analysis and produced water surplus scenarios for Grefsen-Kjelsås that correspond to RCP 4.5 and RCP 8.5. The water surplus scenarios were developed both for 5-year and 20-year rain events resulting in four water surplus scenarios.

A.2. LID Adoption Sub-Model

LID installations are driven by the LID Adoption Structure, which is the core of the model. Before any policy that has an impact on the awareness about LID is introduced, all the households of the catchment sit in the stock of **Unaware Households** (Fig. A.4). The stock is depleted by the **Awareness Rate**, which is the only associated flow, since migration of the population in and out of the catchment is not considered in the model. The Awareness Rate is formulated according to **Eq. A.2**.

$$\textbf{Awareness Rate} = IF(Storm\_Water\_Fee > 0)THEN(MAX\_Awareness\_Rate)ELSE \\ \big(MIN\big(MAX\_Awareness\_Rate; Awareness\_Rate\_from\_Advertising + Awareness\_Rate\_from\_Adopters\big)\big) \tag{A2}$$

$$\textbf{Awareness Rate from Advertising} = \\ 0 + STEP\big(INIT(Unaware\_Households) * Fraction\_of\_Households\_for\_Advertising\_Pulse; Advertising\_Pulse\_Year\_START\big) \\ -STEP\big(INIT(Unaware\_Households) * Fraction\_of\_Households\_for\_Advertising\_Pulse; Advertising\_Pulse\_Year\_END\big) \tag{A3}$$

The formulation for the **Awareness Rate** incorporates the effect of three pressures: the effect of advertising (if subsidies are introduced, the advertising accompanies a subsidy program), awareness from existing adopters (word of mouth) and the effect of stormwater fee. If the stormwater fee is introduced, awareness rate is determined by **MAX Awareness Rate**, given **MIN Time for Awareness Rate** (calibrated to reflect the assumption that it will take a year for all the households to become aware about LIDs) (Table A2). Without SWF, the **Awareness Rate** is the minimum of **MAX Awareness Rate** and the sum of **Awareness Rate from Advertising** and **Awareness Rate from Adopters**.

As the households are becoming aware of LIDs, they are simultaneously distributed among three groups (Fig. A.4). The households with intrinsic interest in LIDs and sufficiently high willingness to pay (WTP) become LID adopters right away and are added to the stock of **Adopters from Attracted** through **Adoption Rate from WTP**. Since this group of the households do not need a financial incentive to install LID, they can be "extracted" from the **Awareness Rate** at **Fraction Adopting from WTP**. It is these households that comprise **observed adoption rates** from advertisement campaigns.

The remaining households within the **Awareness Rate** are of either of two types: some of them have intrinsic interest in LIDs but lower WTP which has to be supplemented with financial incentive to overcome the “affordability barrier” and the others do not have intrinsic interest in LIDs and will not respond to a financial incentive. The first type is accumulated in the stock of **Aware Attracted Non-Adopters (AA)** by taking a fraction of potential adopters from the financial incentive from **Awareness Rate**. These non-adopters can eventually move into the stock of Adopters from Attracted if the financial incentive - whether from the subsidy or from the stormwater fee - is sufficient to overcome the “affordability barrier”. The second type is accumulated in the stock of **Aware Non-Attracted (ANA)** by taking a compliment of **LID Attractiveness** from **Awareness Rate**. These non-adopters can only be motivated to install LID by the stormwater fee. For clarity, **Adopters from ANA** are aggregated separately from **Adopters from Attracted**.

It is important to recognize that the allocation of aware households among the three groups is done by the model assuming the initial MAX LID Attractiveness and WTP (more specifically, the distribution of the households with intrinsic interest around average WTP). However, only the adoption rates are observed. For example, before AA and ANA households begin adopting LIDs, a municipality as a policymaker cannot differentiate between the two groups. The disaggregation of potential adopters into the stocks reflects the assumed underlying distribution of the households in terms of their intrinsic interest in LIDs and WTP for those who exhibit such interest.

Since the **LID Attractiveness** is dynamic in the model, any change in **LID Attractiveness** is accompanied by the corresponding redistribution of the households. The loss of both adopters and non-adopters that reflects lower **LID Attractiveness** adds to the stock of **Aware Non-Attracted** through **from Adopters from Attracted to ANA Rate** and **From AA to ANA Rate**. The increase in LID Attractiveness leads to **Aware Non-Attracted** households moving to the stock of **Aware Attracted Non-Adopters** through **From ANA to AA Rate**. A reduction of financial incentives (subsidy) does not impact attractiveness but redistributes the households from **Adopters from Attracted** to **Aware Attracted Non-Adopters** through **from Adopters to AA Rate**.

The flows for adoption rates are formulated based on adoption potentials associated with each of the portrayed mechanisms. These adoption potentials are determined by the split of the households in terms of their intrinsic interest in LIDs and by the cost-benefit evaluation, given the reference monetary values for incentive policies, SWM regulation policies and WTP. The cost-benefit evaluation is described in the Policy Effects Sub-Model and captured by four corresponding effects: **Effect of WTP on Adoption from Attracted, Effect of Stormwater Fee on Adoption from Attracted, Effect of Subsidy on Adoption from Attracted**, and **Effect of Stormwater Fee on Adoption from Non-Attracted** (see section A.3). The first three effects are adoption potentials formulated as fractions of attracted households and the fourth effect is an adoption potential formulated as a fraction of non-attracted households.

The application of the effects to determine actual adoption rates varies depending on whether an effect is applied to a flow or to a stock, within the scale of all the households in the catchment or within a sub-set of attracted/non-attracted households. As described above, adoption rate associated with the households who have sufficiently high WTP and do not need a financial incentive is governed by **Fraction Adopting from WTP**. This fraction is essentially the **Effect of WTP on Adoption from Attracted**, recalculated relative to the total households, since the adoption fraction is applied to the total households-level Awareness Rate. Since the adoption fraction is applied to the flow, the households that are not subjected to this adoption mechanism are accumulated elsewhere in the model and, once the stock of **Unaware Households** is depleted, cumulative adopters from WTP constitute the fraction of total households that corresponds to the adoption potential indicated by **Fraction Adopting from WTP**.

The realization of adoption potential associated with other mechanisms is formulated differently, since the households are accumulated in the stocks first and adoption potential represents only a sub-set of a respective stock. Once the adoption potential from a given monetary value of incentive policy or SWM regulation is realized, the adoption flow must cease even though the stock still contains households. A generic structure that satisfies such requirements is portrayed in Fig. A.5.

In this structure the adoption rates continues for as long as there are remaining potential adopters associated with a mechanism. For a generic structure, the remaining potential adopters are calculated according to Eq. A.4. The remaining potential adopters are added to the stock of adopters at a pace determined by **Time to Adopt**. Since the remaining potential adopters are calculated within the attracted/non-attracted sub-set of the households, the effects of respective policies determine directly the corresponding adoption fractions.

$$RemPotAdopters = (NonAdopters + Adopters) \times AdoptersFraction - Adopters \tag{A.4}$$

The calculated **Adoption From AA from SWF** is final and enters into **Adoption Rate from AA**. The **Adoption From AA from Subsidy** is final in an unlimited subsidy mode, but is indicated in a limited subsidy mode and enters the **Adoption Rate from AA** in a full or partial amount after it passes the subsidy availability check (see section A.4).

The remaining adoption potential structures for specific sub-sets of households include some modifications relative to the generic structure on Fig. A.5. For example, to account for the fact that attracted households contain households adopting from WTP, Adopters from WTP are subtracted from the adoption potential base in the equations for **Remaining Potential AA Adopters from Subsidy** and from **Stormwater Fee**.

A.3. Policy Effects Sub-Model: Subsidies and Stormwater Fee

The policies are intended to realize the adoption potential, which is indicated by **LID Attractiveness. LID Attractiveness** is conceptually paired with **Willingness to Pay (WTP)**, a variable that captures the intrinsic monetary value that attracted households place on LIDs. This value is formulated based on **LID Cost** and the fraction of the cost that attracted households are willing to cover out of pocket (Table A3).

LID Attractiveness indicates the potential for LID adoption at a point in time. The extent to which the indicated adoption potential is going to be realized is determined by the fraction of LID cost remaining after accounting for Willingness to Pay that is covered by **LID subsidy. Benefit to Cost Ratio** (Eq. A.5equation A.5) is the variable that captures the monetary value associated with LIDs relative to LID cost.

$$BenefittoCostRatio = \frac{(AnnualizedWTP + SWF + AnnualizedSubsidy)}{AnnualizedLIDCost} \tag{A.5}$$

The numerator of the base Benefit to Cost Ratio combines all three potential sources of monetary value for LIDs: Willingness to Pay, Subsidy and Stormwater Fee. Since the stormwater fee is formulated in per-year terms (unit: NOK/household/year), all the other monetary concepts are annualized based on **LID Lifetime** (discussed in section A.1.) and assumed **Interest Rate**.

The extent to which benefit to cost ratio affects the adoption potential is specified by **Elasticity of Adoption to Benefit to Cost Ratio for Attracted**. The effect is smoothed exponentially over **Time to Perceive Costs and Benefits** to account for delays associated with households obtaining knowledge about changes in monetary costs and benefits associated with LIDs and incorporating them into their decisions to install or not to install LIDs. The resulting **Effect of Benefit to Cost Ratio on Adoption from Attracted** is the combined effect of subsidy and stormwater policies. This effect captures that, in the stormwater fee context, many households will need both subsidy and stormwater fee to accrue enough monetary value to close the gap between their willingness to pay for LID and LID cost.

Some households have willingness to pay high enough to balance LID cost without an incentive policy. This fraction of attracted households is driven by willingness to pay alone as a source of monetary value and is captured by the **Effect of WTP on Adoption from Attracted**. The effect is calculated in the same way as the joint effect of stormwater fee and subsidy but based on benefit to cost ratio that has only WTP as a source of monetary value in its numerator (Eq. A.6).

$$BenefittoCostRatiofromWTP = \frac{AnnualizedWTP}{AnnualizedLIDCost} \tag{A.6}$$

In the absence of both incentive policies, the combined effect of all sources of monetary value is comprised entirely of the effect of WTP. In this case, the **Effect of WTP on Adoption from Attracted** is equal to the **Effect of Benefit to Cost Ratio on Adoption from Attracted**. The effect of WTP alone essentially captures the adoption rate typically driven by advertising campaigns. The only condition for realizing this fraction of LID adoption potential is to have a necessary number of households in the stock of **Aware Households**. This target can be achieved by stimulating **Getting Aware Rate**.

The households with the next highest WTP need an additional monetary incentive to balance LID cost, but since their WTP is still high, the stormwater fee is just enough for this purpose. In other words, a certain fraction of attracted households can be motivated to adopt LIDs by stormwater fee alone. This fraction is captured by the **Effect of Stormwater Fee on Adoption from Attracted**, which is calculated in the same way as the joint effect of stormwater fee and subsidy but based on benefit to cost ratio that has only two sources of monetary value in its numerator: **Willingness to Pay** and **Stormwater Fee**Eq. A.7 (equation A.7).

$$BenefittoCostRatiofromWTPandSWF = \frac{(AnnualizedWTP + SWF)}{AnnualizedLIDCost} \tag{A.7}$$

The remaining attracted households with lower willingness to pay will need to be provided a subsidy to be motivated to install LID. The fraction of these households in total attracted households is captured by the **Effect of Subsidy on Adoption from Attracted**. This effect is calculated by subtracting **Effect of WTP on Adoption from Attracted** and **Effect of Stormwater Fee on Adoption from Attracted** from the combined effect of all three motivation sources.

Note that in the context of no stormwater fee, the **Effect of Stormwater Fee on Adoption from Attracted** takes on value zero and the combined effect is comprised entirely of the effect of subsidy and WTP. In this case, the **Effect of Subsidy on Adoption from Attracted** is equal to **Effect of Benefit to Cost Ratio on Adoption from Attracted** net of **Effect of WTP on Adoption from Attracted.**

When the stormwater fee is introduced, the effect of stormwater fee alone is positive, yet, by the formulation of benefit to cost ratios is less than the combined effect. In this case, the **Effect of Stormwater Fee on Adoption from Attracted** indicates the fraction of attracted households with higher willingness to pay for who the stormwater fee provides sufficient motivation to adopt LIDs. The **Effect of Subsidy on Adoption from Attracted** then indicates the fraction of attracted households with lower willingness to pay for who the stormwater fee needs to be supplemented by subsidy.

A separate mechanism in the model captures the effect of stormwater fee on households that are not attracted to LIDs and do not have a positive Willingness to Pay for LIDs. For these households, the only benefit of installing LID is to forgo paying the Stormwater Fee. Therefore, the **Effect of Stormwater Fee on Adoption from Non-Attracted Households** is based on the **Stormwater Fee to LID Cost Ratio**. While the stormwater fee is captured by one representative policy value in the model, the amount of fee paid by an individual household varies depending on the assessed contribution of its property to the stormwater runoff. For simplicity, it is assumed that one LID is expected to be installed per household and that by installing an LID, a household is exempt from paying the entire stormwater fee.

The effect of stormwater fee can be formulated in two ways. The first possibility is to follow the same approach as for attracted households and to specify the **Elasticity of Adoption to Stormwater Fee for Non-Attracted**. According to this formulation, when the stormwater fee completely covers LID cost (**Stormwater Fee to LID Cost Ratio** is one), the **Effect of Stormwater Fee on Adoption from Non-Attracted** induces all the non-attracted households to install LID. Since the properties in the region are distributed in terms of their contribution to runoff and, therefore, in terms of the fee to be paid, some households will be induced to install LID even when **Stormwater Fee to LID Cost Ratio** is below one. The **Elasticity of Adoption to Stormwater Fee for Non-Attracted** captures the extent to which the **Stormwater Fee to LID Cost Ratio**, when it is below one, impacts the adoption by non-attracted households. Similar to other economic effects in the model, this effect is capped at one.

Given that the purpose of the model is to test a general response of the LID adoption to reference stormwater fee policy, the table function is constructed based on the qualitative expert assessments. The table function (Fig. A.6) assumes that 90% of non-attracted households will install LIDs when the Stormwater Fee covers LID cost completely (**Stormwater Fee to LID Cost Ratio** is one). It assumes further that the Stormwater Fee must exceed LID Cost by at least 20% (**Stormwater Fee to LID Cost Ratio** is 1.2) to induced all the non-attracted households to install LIDs. When the Stormwater Fee is 40% of LID Cost, 20% of non-attracted households are expected to install LIDs.

A.4. Stormwater Fee Account Sub-Model

To provide the possibility for simulating LID subsidies that are financially limited to the receipts from SWF, the model contains the structure that integrates the two policies through monetary flows (Fig. A.7).

The stormwater fee from non-adopters is tracked through the flow of **Stormwater Fee Revenues** and is accumulated in the stock of **Stormwater Fee Account**. The total of LID subsidies paid out to households comprises **Expenses from Stormwater Fee Account** that depletes the Stormwater Fee Account stock. The subsidies that are paid out of stormwater fee account are of two types: subsidies for first-time LID installations are associated with the adoption rate and subsidies for repurchases are associated with indicated repurchase rate. Both types of subsidies are subject to financial availability constraint (**Availability of Subsidies**), calculated as **Available Subsidies** relative to **Indicated Subsidies**. The former is determined by the funds available in Stormwater Fee account, given the policy-determined amount of subsidy and **LID Installation per Household**. The latter is the sum of **Subsidies Indicated by Adoption Rate** and **Subsidies Indicated by Repurchase Rate**.

References

Abebe, Y., Adey, B. T., & Tesfamariam, S. (2021). Sustainable funding strategies for stormwater infrastructure management: A system dynamics model. *Sustainable Cities and Society, 64*, Article 102485. https://doi.org/10.1016/j.scs.2020.102485

Akers, J. F., & Yasué, M. (2019). Motivational Crowding in Payments for Ecosystem Service Schemes a Global Systematic Review. *Conservation & Society, 17*(4), 377–389.

Ando, A. W., & Freitas, L. P. C. (2011). Consumer demand for green stormwater management technology in an urban setting: The case of Chicago rain barrels. *Water Resources Research, 47*(12). https://doi.org/10.1029/2011WR011070

Barton, D., Ring, I., & Rusch, G. (2017). Policy Mixes: Aligning instruments for biodiversity conservation and ecosystem service provision. *Environmental Policy and Governance, 27*, 397–403. https://doi.org/10.1002/eet.1779

Barton, D. N., Venter, Z. S., Sælthun, N. R., Furuseth, I. S., & Seifert-Dähnn, I. (2021). Brukerfinansiert klimaberedskap? En beregningsmodell for overvannsgebyr i Oslo. *Vann, 56*(4).

Cote, S. A., & Wolfe, S. E. (2014). Research Article: Assessing the Social and Economic Barriers to Permeable Surface Utilization for Residential Driveways in Kitchener, Canada. *Environmental Practice, 16*(1), 6–18. https://doi.org/10.1017/S1466046613000641

de Gooyert, V. (2019). Developing dynamic organizational theories; three system dynamics based research strategies. *Quality & Quantity, 53*(2), 653–666. https://doi.org/10.1007/s11135-018-0781-y

Dhakal, K. P., & Chevalier, L. R. (2017). Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application. *Journal of Environmental Management, 203*, 171–181. https://doi.org/10.1016/j.jenvman.2017.07.065

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution, 186*(1), 351–363. https://doi.org/10.1007/s11270-007-9484-z

DNB. (2021). Gjennomsnitts-kurser mot NOK. Retrieved from https://www.dnb.no/bedrift/markets/valuta-renter/valutakurser-og-renter/HistoriskeValutakurser/Hovedvalutaer-mndogor/Hovedvalutaer-mndogor.html.

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment, 607-608*, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Elliott, R. M., Motzny, A. E., Majd, S., Chavez, F. J. V., Laimer, D., Orlove, B. S., & Culligan, P. J. (2020). Identifying linkages between urban green infrastructure and ecosystem services using an expert opinion methodology. *Ambio, 49*(2), 569–583. https://doi.org/10.1007/s13280-019-01223-9

Ezzine-de-Blas, D., Corbera, E., & Lapeyre, R. (2019). Payments for Environmental Services and Motivation Crowding: Towards a Conceptual Framework. *Ecological Economics, 156*, 434–443. https://doi.org/10.1016/j.ecolecon.2018.07.026

Forrester, J. W. (1970). Urban Dynamics. *IMR; Industrial Management Review (pre-1986), 11*(3), 67.

Furuseth, I. S., Seifert-Dähnn, I., Azhar, S. Q., & Braskerud, B. C. (2018). Overvann i bebygde strøk - tid for å involvere innbyggerne. *Vann, 53*(4).

Gerber, A. (2017). Why do some Food Availability Policies Fail? A Simulation Approach to Understanding Food Production Systems in South-east Africa. *Systems Research and Behavioral Science, 34*(4), 386–400. https://doi.org/10.1002/sres.2462

Goonetilleke, A., Thomas, E., Ginn, S., & Gilbert, D. (2005). Understanding the role of land use in urban stormwater quality management. *Journal of Environmental Management, 74*(1), 31–42. https://doi.org/10.1016/j.jenvman.2004.08.006

Hoover, F.-A., Meerow, S., Grabowski, Z. J., & McPhearson, T. (2021). Environmental justice implications of siting criteria in urban green infrastructure planning. *Journal of Environmental Policy & Planning, 23*(5), 665–682. https://doi.org/10.1080/1523908X.2021.1945916

Horvat, A., Fogliano, V., & Luning, P. A. (2020). Modifying the Bass diffusion model to study adoption of radical new foods–The case of edible insects in the Netherlands. *PLOS ONE, 15*(6), Article e0234538. https://doi.org/10.1371/journal.pone.0234538

Kea, K., Dymond, R., & Campbell, W. (2016). An Analysis of Patterns and Trends in United States Stormwater Utility Systems. *JAWRA Journal of the American Water Resources Association, 52*(6), 1433–1449. https://doi.org/10.1111/1752-1688.12462

Kukadia, J., Lundholm, M., & Russell, I. (2018). Designing Rain Gardens: A Practical Guide. In U. D. London (Ed.), (pp. 43). London.

Lekkerkerk, W. (2020). *Opportunities to make Grefsen stormwater proof: developing adaptation pathways for the Grefsen district in Oslo, Norway*. (Masters of science). Wageningen University.

Li, H., Gao, H., Zhou, Y., Xu, C.-Y., Ortega, MR. Z., & Sælthun, N. R (2020). Usage of SIMWE model to model urban overland flood: a case study in Oslo. *Hydrology Research, 51*(2), 366–380. https://doi.org/10.2166/nh.2020.068

Lieberherr, E., & Green, O. O. (2018). Green Infrastructure through Citizen Stormwater Management: Policy Instruments, Participation and Engagement. *Sustainability, 10*(6). https://doi.org/10.3390/su10062099

Londoño Cadavid, C., & Ando, A. W. (2013). Valuing preferences over stormwater management outcomes including improved hydrologic function. *Water Resources Research, 49*(7), 4114–4125. https://doi.org/10.1002/wrcr.20317

Luan, B., Yin, R., Xu, P., Wang, X., Yang, X., Zhang, L., & Tang, X. (2019). Evaluating Green Stormwater Infrastructure strategies efficiencies in a rapidly urbanizing catchment using SWMM-based TOPSIS. *Journal of Cleaner Production, 223*, 680–691. https://doi.org/10.1016/j.jclepro.2019.03.028

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., …, & Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience. *Earth's Future, 6*(12), 1638–1659. https://doi.org/10.1029/2018EF000926

Montalto, F. A., Bartrand, T. A., Waldman, A. M., Travaline, K. A., Loomis, C. H., McAfee, C., …, & Boles, L. M. (2013). Decentralised green infrastructure: the importance of stakeholder behaviour in determining spatial and temporal outcomes. *Structure and Infrastructure Engineering, 9*(12), 1187–1205. https://doi.org/10.1080/15732479.2012.671834

Norges Bank. (2020). Interest rates. Retrieved from https://www.norges-bank.no/en/topics/Statistics/Interest-rates/.

Oslo kommune. (2013). *Strategi for overvannhåndtering i Oslo*.

Oslo kommune. (2018). *Norm for blågrønn faktor i boligprosjekter i Oslo*.

Oslo kommune. (2019). *Handlingsplan for overvannshåndtering i Oslo kommune*.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences, 104*(39), 15181. https://doi.org/10.1073/pnas.0702288104

Rahmandad, H., & Sterman, J. (2008). Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models. *Management Science, 54*(5), 998–1014. https://doi.org/10.1287/mnsc.1070.0787

Richardson, G. P. (1991). System Dynamics: Simulation for Policy Analysis from a Feedback Perspective. In P. A. Fishwick, & P. A. Luker (Eds.), *Qualitative Simulation Modeling and Analysis* (pp. 144–169). New York, NY: Springer New York.

Ring, I., & Barton, D. (2015a). Economic instruments in policy mixes for biodiversity conservation and ecosystem governance. In J. Martinez-Alier, & R. Muradian (Eds.), *Handbook of Ecological Economics* (pp. 413–449). Cheltenham: Edward Elgar.

Ring, I., & Barton, D. (2015b). Economic instruments in policy mixes for biodiversity conservation and ecosystem governance. In (pp. 413-449).

Schifman, L. A., Herrmann, D. L., Shuster, W. D., Ossola, A., Garmestani, A., & Hopton, M. E. (2017). Situating Green Infrastructure in Context: A Framework for Adaptive Socio-Hydrology in Cities. *Water Resources Research, 53*(12), 10139–10154. https://doi.org/10.1002/2017WR020926

Shaw, B. R. (2011). Predicting Intent to Install a Rain Garden to Protect a Local Lake: An Application of the Theory of Planned Behavior. *Journal of extension, 49*(4), 14–2011. v.2049 no.2014.

Shin, D. W., & McCann, L. (2018). Enhancing Adoption Studies: The Case of Residential Stormwater Management Practices in the Midwest. *Agricultural and Resource Economics Review, 47*(1), 32–65. https://doi.org/10.1017/age.2017.3

Sælthun, N. R., Barton, D. N., & Venter, A. (2021). *REO: estimering av overflateavrenning fra urbane felt. Beregningsgrunnlag for et arealdifferensiert overvannsgebyr*.

Tasca, F. A., Assunção, L. B., & Finotti, A. R. (2018). International experiences in stormwater fee. *Water Science and Technology, 2017*(1), 287–299. https://doi.org/10.2166/wst.2018.112

Thurston, H. W., Taylor, M. A., Shuster, W. D., Roy, A. H., & Morrison, M. A. (2010). Using a reverse auction to promote household level stormwater control. *Environmental Science & Policy, 13*(5), 405–414. https://doi.org/10.1016/j.envsci.2010.03.008

Ureta, J., Motallebi, M., Scaroni, A. E., Lovelace, S., & Ureta, J. C. (2021). Understanding the public's behavior in adopting green stormwater infrastructure. *Sustainable Cities and Society, 69*, Article 102815. https://doi.org/10.1016/j.scs.2021.102815

Zhao, J. Z., Fonseca, C., & Zeerak, R. (2019). Stormwater Utility Fees and Credits: A Funding Strategy for Sustainability. *Sustainability, 11*(7). https://doi.org/10.3390/su11071913