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Cost to society from infiltration and inflow to wastewater systems

Anna Ohlin Saletti [a,b,*], Andreas Lindhe [a], Tore Söderqvist [c], Lars Rosén [a]

[a] Department of Architecture and Civil Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden
[b] Department of Sustainable Waste and Water, City of Gothenburg, 41502 Gothenburg, Sweden
[c] Holmboe & Skarp AB, 14896 Sorunda, Sweden

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ABSTRACT

Water from infiltration and inflow to wastewater systems is an extensive problem causing costs to society in various ways. Comprehensive methods for supporting decisions on how to efficiently mitigate the problems in a sustainable manner are, however, missing today. This paper presents a novel risk-based model to assess the cost to society from infiltration and inflow to wastewater systems by monetising effects related to treatment of wastewater, pumping, combined sewer overflows, and basement flooding. The present value is calculated for a specified time horizon and discount rate, using a cost-benefit analysis approach. To acknowledge the various uncertainties, a probabilistic approach is applied where probability distributions represent the input variables. The model is shown to be applicable by illustrating its use in a case study area in Gothenburg, Sweden. Main results from the case study show that most of the costs are related to investments at the wastewater treatment plant and restoration due to basement flooding events. Sensitivity analyses show that the result is highly dependent on factors such as the volume of infiltration and inflow water, the share of basement flooding, and the discount rate. Using expert elicitation to quantify input data is also illustrated and shown to be a valuable method. The presented model fills an important research knowledge gap and will facilitate a more sustainable and comprehensive handling of water from infiltration and inflow.

1. Introduction

Wastewater systems provide society with vital services, but suboptimal design may result in unnecessary costs for society. Sanitary sewage is the most obvious component of the flow reaching a wastewater treatment plant (WWTP). However, a large share of the total annual volume usually consists of water from infiltration and inflow (I/I-water). In this paper the term I/I-water concerns all water in a wastewater system that is not sanitary sewage. No distinction is made regarding if the water originates from infiltration or inflow and I/I-water in both combined and separate systems is considered. I/I-water can be a result of a conscious system design such as in a combined system. However, I/I-water can also come from unintended sources such as misconnections or inflow of groundwater through leaky pipes. In a study by Clementson et al. (2020), it was shown that 20–70% of the annual flow to the investigated Swedish WWTPs consisted of I/I-water and the share is dependent on, e.g. if the system is combined or separated, its age and state as well as precipitation levels and hydrogeological conditions.

Different effects may occur depending on the characteristics of the I/I-water. A baseflow of I/I-water results in a continuous treatment need at the WWTPs whereas rain dependent I/I-water can result in combined sewer overflows (CSOs) and basement flooding events. Hence, the effects of I/I-water are either relatively consistent or occur occasionally. The latter effects can be regarded as risks made up by events that occur with a certain probability and are associated with consequences, as first formulated by Kaplan and Garrick (1981). The effects of I/I-water impact the society, resulting in costs for the water utilities ("internal costs" henceforth) and also costs incurred by other parts of society (i.e., externalities, "external costs" henceforth). The latter typically include negative impact on society because of environmental and health effects (e.g., Sola et al., 2020). An analysis of the total cost to society should thus aim at including all internal and external costs. Further, numerous uncertainties, both aleatory and epistemic, that should not be overlooked, exist related to I/I-water, e.g. due to variation in weather and climate or because of limited efficiency of the methods used to localise and quantify I/I-water.

Effects of I/I-water have previously been monetised as part of decision support models. As an example, Sola et al. (2020) monetise the cost of I/I-water including internal costs and external costs due to environmental and health effects. In several other decision support models, e.g.

* Corresponding author.
E-mail address: anna.ohlin.saletti@chalmers.se (A. Ohlin Saletti).

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Fig. 1. Approximate location of the case study area in the City of Gothenburg, Sweden.

by Diogo et al. (2018) and Davalos et al. (2018), the effects of I/I-water are monetised based on the internal financial cost of treatment and transportation. Others have monetised individual effects of I/I-water, e.g. Korving et al. (2009) present a risk-based method where the cost of CSOs is monetised considering uncertainties, and Torgersen and Navrud (2018) perform a willingness to pay (WTP) study to assess the inconvenience cost of basement flooding events. However, according to our knowledge, no model exists that comprehensively quantifies the cost of I/I-water using a risk-based approach including uncertainties as well as external costs related to both environmental and health effects. The overall aim of this paper is to present such a risk-based model for calculating the cost to society of I/I-water to wastewater systems. Knowledge of the cost to society from I/I-water allows for a cost-benefit analysis (CBA) of interventions to reduce I/I-water, considering both project internal and external effects in society. Given the size of the contribution of I/I-water to wastewater systems, the development and application of CBA would provide a much needed basis for prioritisation of society's limited resources for managing I/I-water. To reach the overall aim, the paper has the specific objectives to present (1) an approach to monetise costs related to I/I-water at the WWTP and due to pumping, CSOs, and basement flooding events, (2) how the present value can be calculated choosing time horizon and discount rate, (3) how expert elicitation can be used to collect information about the input variables and their uncertainty, (4) how the uncertainty of the result and the input variables can be assessed using uncertainty and sensitivity analysis. A case study illustrating application of the model is performed for a catchment area in Gothenburg, Sweden.

2. Case study

The case study area is located in the central parts of Gothenburg, Sweden (Fig. 1). All wastewater from the city of Gothenburg is directed to Rya WWTP, built in 1972, that serves a population of 800 000 (Gryaab, 2022). Substantial upgrades of the WWTP are planned for the near future and to be finished in 2036. Around 30% of the total length of the wastewater system in Gothenburg is combined.

The case study location was chosen since I/I-water is a large problem in the area. Moreover, it is included as a sub-area in an existing hydrological and hydraulic model (Future City Flow, 2022) used by the water utility which facilitated the extraction of flow data. The case study area is approximately 310 hectares in a densely populated area with around 35 000 connected person equivalents. Approximately 70% of the wastewater system in the case study area is combined and it contains several discharge points for CSOs leading to recipients. The housing is mixed consisting of both detached, single family houses, apartment buildings, and public buildings.

According to the current Swedish standards for dimensioning of sewage pipes, the combined system in the case study area should be dimensioned to handle a rain with a five-year return period in regards of CSOs and a rain with a 10-year return period concerning basement flooding (Swedish water, 2004). The return period corresponds to the recurrence interval, i.e., the time until a given event is expected to occur (e.g., Singh et al., 2007). For pipes built after 1976 but before 2004 the combined systems should be dimensioned for a rain with a five-year return period (VAV, 1976). Most of the combined system was, however, built before 1976, and hydraulic network modelling performed by the City of Gothenburg shows that most of the pipes in the combined system would be able to handle a rain with a one-year return period but significantly fewer can handle a 10-year return period rain.

3. Method

3.1. Cost of I/I-water

To be able to compare costs that occur at different points in time during a longer time horizon (several years), discounting as used in CBA is applied (Boardman et al., 2017). The present value (*PV*) is:

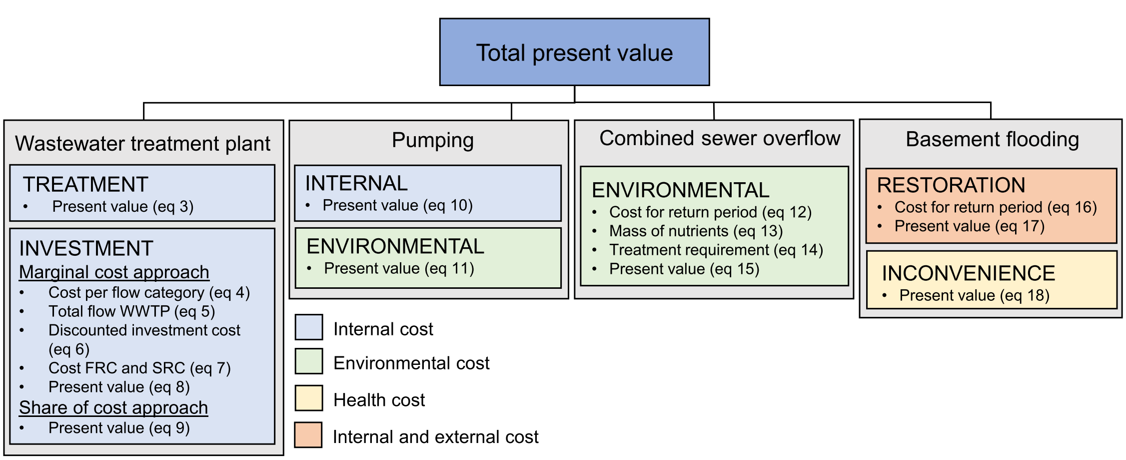

Fig. 2. Overview of costs included in case study and corresponding equations.

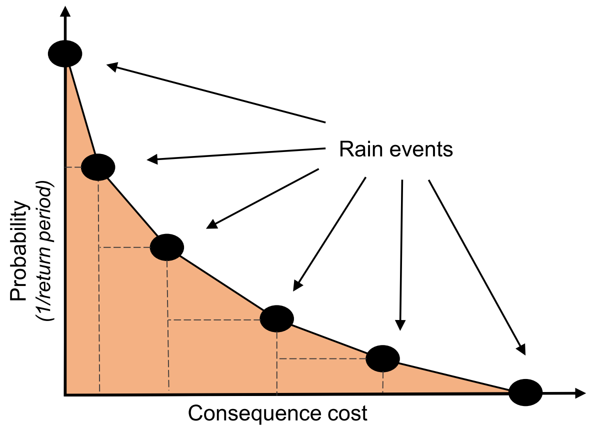

Fig. 3. Risk cost represented by the orange area made up from a few chosen rain events based on different return periods.

$$PV = \sum_{t=0}^{T}\left(C_t * \frac{1}{(1+r)^t}\right) \quad (1)$$

where T is the time horizon including the years t $(t=0 \ldots T)$, C_t the cost year t, and r the social discount rate.

When applying the model on the case study area, effects at the WWTP and effects due to pumping, CSOs, and basement flooding events are included. Related to these effects seven costs which represent both internal and external costs, were chosen to be monetised (Fig. 2). The *PV* for each cost was calculated and then the *PVs* were summed to obtain the total *PV*.

The included effects also represent both continuous *base effects* occurring under normal conditions and *risks* due to unwanted events. The risks are represented by the function of the frequency of rains with specific return periods and the corresponding economic consequences. Further, the risk costs are calculated using the integral of this function. When applied on the case study area, data availability implies limitations in the possibility to model the consequences for all possible probabilities. Therefore, instead of calculating the continuous cost function, the calculations are simplified by approximating the total risk cost by choosing a few return periods and calculating the sum of the areas of the triangles and rectangles (Fig. 3).

To account for climate change affecting the precipitation during the time horizon a climate factor was introduced. As a simplification, a single climate factor was chosen that represents different kinds of changes in I/I-water volumes. The yearly change (yc_{cf}) due to the climate factor is:

$$yc_{cf} = cf^{\frac{1}{T}} - 1 \quad (2)$$

where cf is a climate factor expressing the expected change in climate during the time horizon T.

In the following sections the calculations of the costs of I/I-water included in the case study are presented. The costs are expressed in monetary units (MU) and all notations are compiled in Appendix A.

3.1.1. *Treatment (WWTP)*

The *PV* of treatment of I/I water $(PV_{WWTP_{tr}})$ [MU] for the time horizon is:

$$PV_{WWTP_{tr}} = \sum_{t=0}^{T} V_{I/I_t} * \left(1 + yc_{cf}\right)^t * c_{tr} * \left(1 + \left(\frac{c_{tr}}{c_{tr} * inc_{tr}}\right)^{\frac{1}{T}} - 1\right)^t * \frac{1}{(1+r)^t} \quad (3)$$

where V_{I/I_t} [m^3] is the volume of I/I-water to the WWTP from the case area year t, c_{tr} [MU/m^3] the cost for treating I/I-water at the WWTP, and inc_{tr} [-] (unitless variable) a factor expressing how much the cost to treat I/I water is expected to increase in real terms during the time horizon T.

3.1.2. *Investment (WWTP)*

Two approaches for calculating the investment cost at the WWTP are presented, called the “marginal cost approach” and the “share of cost approach”. The marginal cost approach assumes different costs for different flows and is suitable when assessing the investment costs for an area which constitutes a smaller part of the whole catchment area to a WWTP. The share of cost approach assumes equal costs independent of the size of the flow and must be used if applied on the whole catchment area for a WWTP. In the case study the marginal cost approach is used in the main analysis and the share of cost approach as a scenario in the sensitivity analysis.

3.1.2.1. Marginal cost approach. In Gothenburg, previous studies have been performed regarding the cost of I/I-water due to investments in the WWTP. These cost estimations acknowledge the flow variation to the WWTP over a year where a smaller share of the total volume consists of sanitary sewage and the rest of I/I-water (Fig. 4). Still the WWTP must be prepared to handle the highest flows even though they might only occur a few days per year. Further, investments at the WWTP correspond to different flow capacities and hence to different sizes of flows. Therefore, the cost of I/I-water is calculated using the share of investment costs corresponding to the capacity needed to manage the flow of

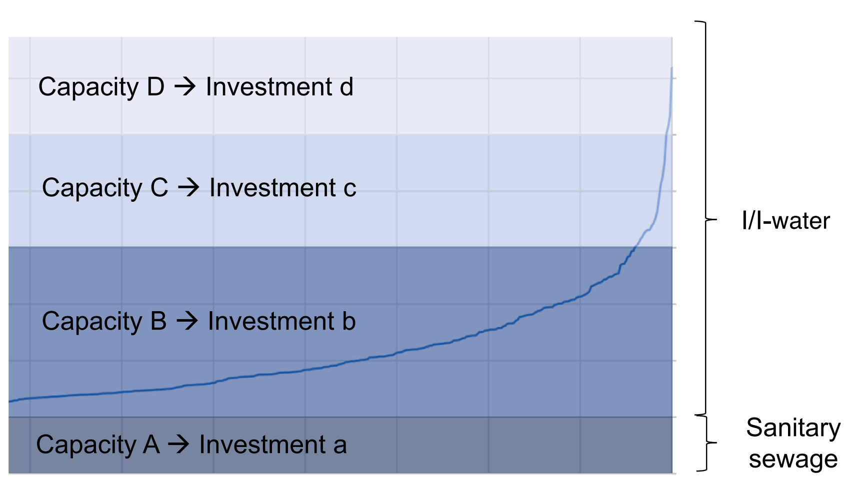

Fig. 4. Schematic figure of accumulated flow to a WWTP. Capacity A corresponds to the sanitary sewage while capacity B to D correspond to I/I-water of different flows.

I/I-water.

The investment cost for a flow category (c_f) [MU/m^3] is:

$$c_f = \frac{inv_{disc} * s_{invf}}{V_{WWTP} * s_{v_f}} \tag{4}$$

where inv_{disc} [MU] is the discounted investment cost over the time period, s_{invf} [-] the share of investment corresponding to flow category *f*, V_{WWTP} [m^3] the total volume reaching the WWTP during the time horizon, and s_{v_f} [-] the share of volume reaching the WWTP in flow category *f* .

The total volume reaching the WWTP (V_{WWTP}) is:

$$V_{WWTP} = \sum_{t=0}^{T} V_{WWTP_t} * (1 + yc_{cf})^t \tag{5}$$

where V_{WWTPt} [m^3] is the total volume to the WWTP in year *t*.

The discounted investment cost inv_{disc} [MU] is:

$$inv_{disc} = \sum_{t=0}^{T} \frac{inv_t}{(1+r)^t} \tag{6}$$

where inv_t [MU] is the investment cost for year *t*.

To obtain the incoming flow as well as the percentage that consists of sanitary sewage or originate from slow response components (SRC) or fast response components (FRC) from the included areas result from previous modelling was used. The used model is a well-calibrated and coupled hydrological and hydraulic network model of the Gothenburg sewage system.

The cost for FRC (c_{FRC}) [MU/m^3] is:

$$c_{FRC} = \frac{\sum_{a=1}^{A} \left(area_a * \sum_{f=1}^{F} c_f * s_{a_f} \right)}{\sum_{a=1}^{A} area_a} \tag{7}$$

where *A* is the number of areas where FRC is monitored including the areas a(a=1…a), $area_a$ [m^2] the area of *a, F* the number of flow intervals, and s_{a_f} [-] the share of flow in flow interval *f* reaching the WWTP from area *a*. The cost for SRC (c_{SRC}) [MU/m^3] is calculated equivalently.

The *PV* of investment due to I/I-water at the WWTP (PV_{WWTP_i}) [MU] is:

$$PV_{WWTP_i} = V_{I/I_t} * (SRC_t * c_{SRC} + FRC_t * c_{FRC}) \tag{8}$$

where SRC_t [-] is the share of SRC year t from the case area and FRC_t [-] the share of FRC year *t* from the case area.

3.1.2.2. Share of cost approach. Using the share of cost approach, the PV of the investment cost due to I/I-water at the WWTP (PV_{WWTP_i}) [MU] is:

$$PV_{WWTP_i} = inv_{disc} * \frac{V_{I/I}}{V_{WWTP}} \tag{9}$$

$V_{I/I}$ [m^3] is the total volume reaching the WWTP from the case area during the time horizon. $V_{I/I}$ is calculated according to Eq. (5) but using V_{I/I_t} instead of V_{WWTPt}.

3.1.3. Internal pumping cost

The PV of the internal pumping cost (PV_{Pin}) [MU] is:

$$PV_{P_{in}} = \sum_{t=0}^{T} V_{I/I_t} * (1 + yc_{cf})^t * E_p * c_{p_{in}} * \frac{1}{(1+r)^t} \tag{10}$$

where E_p [kWh/m^3] is the energy consumption for pumping the I/I-water and $c_{p_{in}}$ [MU/kWh] the internal cost for pumping I/I-water per energy unit.

3.1.4. Environmental pumping cost

The PV of the environmental cost of pumping I/I-water ($PV_{P_{env}}$) [MU] for the time horizon is:

$$PV_{P_{env}} = \sum_{t=0}^{T} V_{I/I_t} * (1 + yc_{cf})^t * (E_p + E_{lift}) * c_{CO2_t} * yc_{CO2} * e_{CO2} * \frac{1}{(1+r)^t} \tag{11}$$

where E_{lift} [kWh/m^3] is the energy needed to lift the I/I-water to the WWTP (included in internal treatment cost and thus not in the internal pumping cost), c_{CO2} [MU/CO_2-eq] the cost per CO_2-eq for year *t*, yc_{CO2} [-] the yearly change in the cost of CO_2 equivalents, and e_{CO2} [CO_2-eq/kWh] the number of CO_2 equivalents per kWh.

3.1.5. Combined sewer overflows

The annual cost of CSOs (R_{CSO_t}) [MU] is calculated as a risk cost for rains with different return periods with corresponding costs, see Fig. 3. The consequence costs are based on WTP studies of reaching good ecological status related to removal of phosphorus and nitrogen, but the removal method is not specified. The cost of CSOs for a specific return period ($C_{rp_{CSO}}$) is:

$$C_{rp_{CSO}} = \frac{M_{rp_{CSO}}}{\tau} * WTP_{gs} * s_n \tag{12}$$

where $M_{rp_{CSO}}$ [kg] is the mass of phosphorus and nitrogen in CSO for return period rp_{CSO}, τ [kg/yr] the mass of phosphorus and nitrogen to be removed to reach their corresponding target levels, WTP_{gs} [MU] the WTP to reach good status in recipients, and s_n [-] the share of the good status that is fulfilled for the recipients by reaching the target levels of phosphorus and nitrogen.

The mass of nutrients in the CSO ($M_{rp_{CSO}}$) [kg] for the return period *rp* is:

$$M_{rp_{CSO}} = \left(V_{ss_{rp_{CSO}}} * P_{ss} + V_{sw_{rp_{CSO}}} * P_{sw} \right) * P_{PO_4eq} + \left(V_{ss_{rp_{CSO}}} * N_{ss} + V_{sw_{rp_{CSO}}} * N_{sw} \right) * N_{PO_4eq} \tag{13}$$

where $V_{ss_{rp_{CSO}}}$ [m^3] is the volume of sanitary sewage in CSOs for return period rp_{CSO}, P_{ss} [kg/m^3] the concentration of phosphorus in sanitary sewage, $V_{swrp_{CSO}}$ [m^3] the volume of stormwater in CSOs for return period rp_{CSO}, P_{sw} [kg/m^3] the concentration of phosphorus in stormwater, P_{PO_4eq} [-] a factor to convert phosphorus to PO_4-equivalents, N_{ss} [kg/m^3] the concentration of nitrogen in sanitary sewage, N_{sw} [kg/m^3] the concentration of nitrogen in stormwater, N_{PO_4eq} [-] a factor to convert nitrogen to PO_4-equivalents.

The treatment requirement (t_r) [-] is:

$$t_r = t_{r_P} * P_{PO_4eq} + t_{r_N} * N_{PO_4eq} \tag{14}$$

where t_{r_P} [kg P/yr] is the treatment requirement for phosphorus and t_{r_N} [kg N/yr] the treatment requirement for nitrogen.

The PV of CSOs (PV_{CSO}) [MU] for the time horizon is:

$$PV_{CSO} = \sum_{t=0}^{T} R_{CSO_t} * (1 + yc_{cf})^t * \frac{1}{(1+r)^t} \tag{15}$$

3.1.6. Restoration (basement flooding)

The annual cost of basement flooding (R_{BF_t}) [MU] is calculated as a risk cost for rains with different return periods with corresponding costs, see Fig. 3. The cost for a specific return period ($C_{rp_{BF}}$) [MU] is:

$$C_{rp_{BF}} = s_{rp_{BF}} * U_{BF} * f_{U_{BF}} * s_{flood} * s_{base} * \sum_{b=1}^{B} cb_b * NB_b \tag{16}$$

where $s_{rp_{BF}}$ [-] is the share of basements being flooded during a rain with return period *rp*, s_{flood} [-] the share of buildings in the case study area

Table 1
Overview of elicitation workshops.

Workshop	Theme	Participants	Type of assessment
WS-A	WWTP	Four experts	Full SHELF-protocol workshop. Followed by elicitation on email.
WS-B	CSOs	Three experts	Full SHELF-protocol workshop. Followed by elicitation on email.
WS-C	Attributes of case study area	Three experts	Full SHELF-protocol workshop. Followed by minimal assessment.
WS-D	General variables and energy	Project team	Minimal assessment.

where basement flooding can occur due to the sewer system, U_{BF} [-] a scaling factor due to the building characteristics in the area, $f_{U_{BF}}$ [-] a scaling factor depending on the return period, B the number of building types with different restoration cost, s_{base} [-] the share of buildings with basements in the area where basement flooding events can occur, cb_b [MU/building] the cost of a basement flooding for building type b, and NB_b the number of buildings of building type b.

The PV of the restoration cost of basement flooding events ($PV_{R_{BF}}$) for the time horizon is:

$$PV_{R_{BF}} = \sum_{t=0}^{T} R_{BF\,t} * \left(1 + yc_{cf}\right)^t * \frac{1}{(1+r)^t} \tag{17}$$

3.1.7. Inconvenience (basement flooding)

The annual inconvenience cost of basement flooding events is based on a WTP study by Torgersen and Navrud (2018) showing that households living closer to a previous basement flooding are willing to pay more to avoid a flooding for themselves. This WTP is separated from the restoration cost as it only concerns the insecurity of getting a flooding and not insurance or other restoration costs.

The PV of the inconvenience of basement flooding events ($PV_{BF_{in}}$) [MU] is:

$$PV_{BF_{in}} = \sum_{t=0}^{T} s_{base} * \sum_{z=1}^{Z} h_z * \ WTP_{BF_z} * \frac{1}{(1+r)^t} \tag{18}$$

where Z is the number of zones z $(z{=}1\ldots Z)$ in different distance intervals from a previous basement flooding, h_z the number of detached, single-family houses in zone z, and WTP_{BF_z} [MU] the WTP per household in detached houses to avoid basement flooding in zone.

3.2. Input variables

Quantification of most input variables was performed using results from hydrological and hydraulic modelling or expert elicitation (see Section 3.3). Additionally, a few variables were quantified using results from previous studies. The approach for quantification of each variable is presented in Appendix B together with the input data but important choices and clarifications regarding some of the input variables are presented below.

The input variables were defined using probability distributions to account for uncertainties. Using Monte Carlo simulation (e.g., Metropolis & Ulam, 1949), performed in Excel with the add-in software @Risk (v.8.2) the uncertainty of the result was assessed. All simulations in the case study were performed using 100 000 iterations. To verify this choice 10 simulations were run and the standard deviation of the median of the PV of the total cost was calculated.

All monetary amounts are stated in Swedish kronor (SEK) in 2021 prices if not otherwise stated. 1 SEK approximately corresponds to 0.1 EUR (2022). A discount rate of 3.5% was used in the case study based on a recommendation from the Swedish transport administration (2020) and the climate factor (cf) 1.25 was used as recommended by Swedish Water (2016). A time horizon of 100 years was chosen for this case study since components in the wastewater piping system often are assumed to last for 100 years and also to be able to include investments at the WWTP in the more distant future.

The volumes of I/I-water in the case study were obtained using the web-based tool Future City Flow (Future City Flow, 2022; Nivert et al., 2019) which is based on the well-calibrated and coupled hydrological and hydraulic network model of the Gothenburg sewage system. The model was run for 18 years and the total volume summarised for each year. The annual volumes were then fitted to probability distributions.

Using the same model, data regarding CSOs were obtained concerning volumes of discharged sanitary sewage and stormwater for each discharge point for rainfall with the return periods one week, one month, half a year, one year, five years, 10 years, and 20 years. Regarding the share of basements being flooded data from a previous study (Rosén & Nimmermark, 2018), including results from hydrological and hydraulic modelling of two other case areas in Gothenburg, was used. Rainfall with return periods one year, two years, five years, 10 years, 20 years, 50 years, 100 years, and 200 years were considered in these calculations.

The cost of CO_2 equivalents was assumed to vary over the time horizon. The electricity production sector is a part of the EU greenhouse gas emission trading system, and it was assumed to remain so until 2031. Following Johansson and Kriström (2018), the price of emission rights was therefore used as the cost of CO_2 equivalents during 2021-2031. The median for this period was assumed to be 0.8 SEK/kg. After 2031, the cost of CO_2 equivalents was assumed to have converged to the social cost of carbon as reviewed by Isacs et al. (2016), irrespective of whether the trading system would still be in function or have been replaced by another policy instrument. The median for 2022-2031 was set to 6.31 SEK/kg, according to the intermediate scenario investigated by Isacs et al. (2016). The uncertainty of the cost during 2021-2031 was estimated as a uniform distribution varying from the current value and the estimate based on high climate sensitivity presented by Isacs et al. (2016). The uncertainty of the cost during 2032-2121 is estimated as a pert distribution with the minimum of the intermediate scenario and the maximum of the high climate sensitivity scenario.

3.3. Expert elicitation

Expert elicitation is useful when information about input variables needed in a model and its corresponding uncertainties is missing (e.g., Cooke, 1991; Dias et al., 2018). Different kinds of protocols exist to perform the elicitation scientifically and structured to avoid common biases, described by e.g. Tversky and Kahneman (1974). The well-established Sheffield Elicitation Framework (SHELF) (O'Hagan et al., 2006; Gosling, 2018) was used as a basis for the expert elicitation in the case study.

In Appendix B it is indicated which variables were quantified using expert elicitation. Because of the large number of quantities of interest (QoIs) to be elicited, the elicitation process was divided into four themes including four workshops (Table 1). Full SHELF workshops were performed for the QoI determined by the project team to be the most important. Additionally, elicitations were performed individually for some of the QoIs and communicated by email after the workshops. The experts were then asked to do the same set of judgements, following the first steps in the Probabilistic Delphi method (Oakley & O'Hagan, 2019) and the judgements were later put together using a linear pool method. For the rest of the QoI, minimal assessment was performed (Oakley & O'Hagan, 2019) by the project team or in a few cases, when the experts

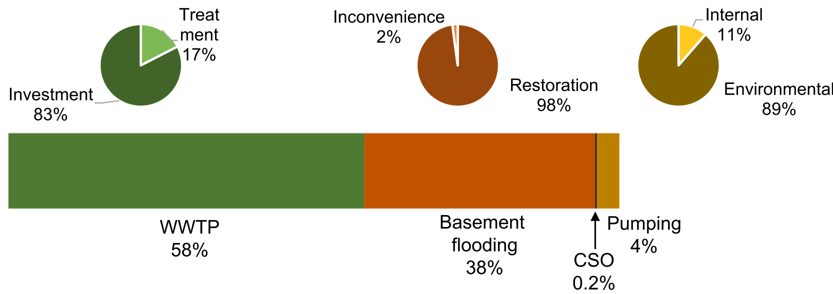

Fig. 5. The proportion of different categories based on medians of PV of cost categories.

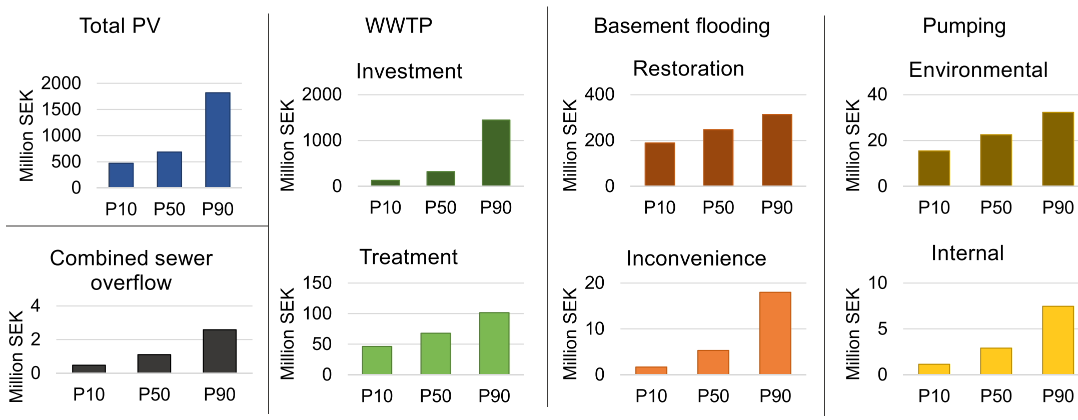

Fig. 6. PV of 10th, 50th, and 90th percentiles for the cost categories.

judged that a joint elicitation could not be performed, by individual experts after a workshop.

The selection of experts for each theme was performed to achieve a group with diversified experience and experts willing to share their knowledge and listen to other opinions. When selecting the experts for WS-A, it was considered important that the experts were not part of the stakeholder organisations. The stakeholders at the WWTP and the water utility were instead invited to provide written background evidence that was provided to the experts. The experts were all consultants with long experience of working with investments at WWTPs and in some cases also with specific knowledge about Rya WWTP. Regarding WS-B, experts were selected representing different stakeholders in the city (the water utility, the environmental department of the City of Gothenburg, and county administrative board). This served to cover different knowledge and ways of assessing the condition of the recipients. For WS-C the experts were selected to cover a broad knowledge about water and sewage systems in general as well as the specific system in Gothenburg. Two senior experts, one from the water utility and one consultant, were selected together with one GIS expert from the water utility.

Prior to the workshops the experts were briefed about the QoIs through a background document. They were also informed about the SHELF-method and asked to provide information about themselves and their expertise. Further, in the beginning of each workshop the experts were trained in the method through an extensive elicitation practice round. During the workshops, the experts were asked to give individual judgements about their lower limit, upper limit, median, lower quartile, and upper quartile for the first QoI. The individual distributions where then visualised using online apps (Oakley, 2022) for elicitation where the best fitting distribution was chosen by the app.

After discussing the individual distributions, the expert group was asked to do a consensus judgement which was also visualised together with the best fitting distribution. After modification by the experts to fit their joint judgement, a distribution was decided upon and the next QoI elicited using the same process. The chosen distributions were later used in the model but in those cases where the visualisation tool suggested distributions that were not available in @Risk, the best available alternative option was chosen instead.

3.4. *Sensitivity analysis*

The contributions to the uncertainty of the result were assessed by means of sensitivity analysis. To evaluate how the input variables were correlated with the total PV, Spearman's rank-order correlation was used. This correlation makes it possible to evaluate the non-linear relationship between variables while requiring monotonicity. To further check the sensitivity of the model, scenario analysis was performed including those variables where it was considered not suitable to assign probability distributions. Scenarios were set up with varying discount rates and climate factors as well as using the "share of cost approach" for calculating the investment cost at the WWTP. Further, a scenario was modelled where more buildings than the detached houses were considered when calculating the inconvenience cost of basement flooding events. The data used in the sensitivity analyses can be found in Appendix C.

4. Case study results

In Fig. 5, the proportion of the different cost categories are presented based on medians of the simulation results. It is shown that most of the total *PV* originates from costs related to the WWTP and to basement flooding events. The cost at the WWTP mostly consists of investment costs and restoration costs make up most of the cost of basement flooding events.

The total *PV* and the *PV* for the different cost categories are shown in Fig. 6. The median of the total *PV* (P50) is approximately 687 million SEK. The 10th percentile is 32% lower than the median value (470 million SEK) and for the 90th percentile 165% higher (1 819 million SEK). The mean of the medians of the *PV* of the total cost for the 10

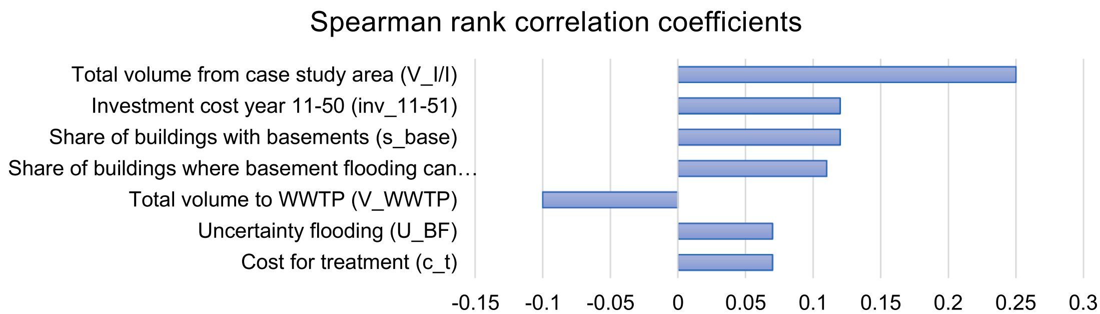

Fig. 7. Spearman rank correlation coefficients.

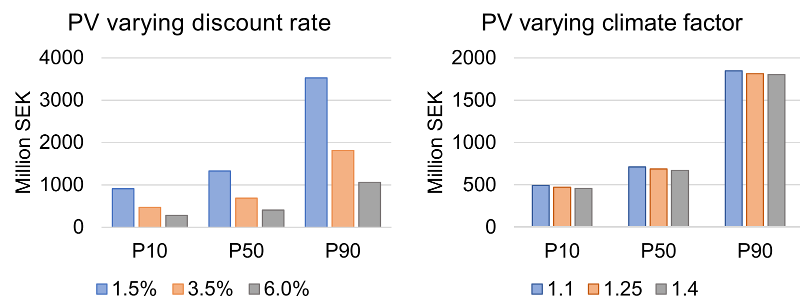

Fig. 8. Sensitivity analyses showing the effect of different discount rates and climate factors on the total PV.

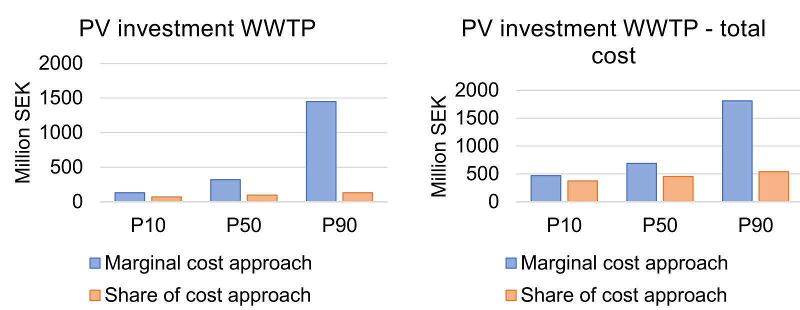

Fig. 9. Result from sensitivity analysis using different approaches to calculate the investment cost. Left diagram shows only the *PV* of the investment cost and the right shows how the variation affects the total *PV*.

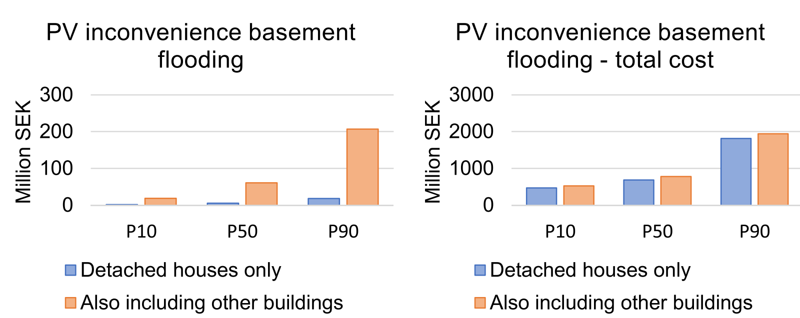

Fig. 10. Result from sensitivity analyses including only detached houses or also apartment buildings/commercial buildings in calculation of inconvenience cost. Left diagram shows only the *PV* of the inconvenience cost and the right shows how the variation affects the total PV.

simulations with 100 000 iterations was 689 million SEK and the standard deviation 0.8 million SEK which is 0.12 % of the mean. Hence, the choice of using 100 000 iterations is considered sufficient.

The Spearman rank correlation coefficients for the eight most strongly correlated input variables for the total *PV* are shown in Fig. 7. The volume of I/I-water has the highest correlation coefficient and thus affects the uncertainty in the *PV* the most.

The result from the scenario analyses with varying discount rates and climate factors is shown in Fig. 8. The median *PV* of the total cost is 93% higher if using a discount rate of 1.5% instead of 3.5%, and 41% lower if using a discount rate of 6.0% instead of 3.5%. Regarding the climate factor, the *PV* of the total cost is 3% higher for the median if using the climate factor 1.1 instead of 1.25, and 3% lower if using the climate factor 1.4 instead of 1.25.

The result from the sensitivity analysis where the share of cost approach was used instead of the marginal cost approach to calculate the investment cost at the WWTP is shown in Fig. 9. For the median the *PV* for the investment cost is 320 million SEK using the marginal cost approach and 96 million SEK using the share of cost approach. The *PV* of the total cost is hence 34% lower when using the share of cost approach.

The result from the scenario where apartment, commercial, and public buldings were added to the inconvenience cost of basement flooding events is presented in Fig. 10. For the median, the inconvenience cost is 11 times higher when not only including detached houses. However, when looking at the total result including these buildings only makes the *PV* 11% higher.

5. Discussion

5.1. Universality of model and case study result

This paper presents a risk-based model for calculating the cost of I/I-water including internal and external costs as well as uncertainty and to demonstrate how it can be used, a case study is included. However, other costs of I/I-water could have been added in the case study and the monetising of those included could have been performed using other approaches. A vast number of costs of I/I-water are conceivable and when applying the model in other contexts, costs should be included based on their importance for the stakeholders and on the specific area conditions. Examples of additional costs of I/I-water that can be included are those due to environmental impact from chemicals used in treatment processes, subsidence at roads, or decreased capacity to do new sewage connections. Some additional costs might be difficult to monetise, but if considered important they should at least be described qualitatively.

The result of the case study showed that most of the cost related to I/I-water was due to investments at the WWTP and basement flooding events. In comparison, the cost for CSOs and pumping was negligible. The result, showing a very small impact from CSOs, was unexpected and it would be very interesting to investigate if the cost would be larger if using another approach for monetising the effect of CSOs. In the case study, the monetisation was based on the WTP for inhabitants to reach good status of the recipients and then expressed in SEK/kg released PO_4 equivalents. For validation this cost, which turned out to be around 300 SEK/kg released PO_4 equivalent, can be compared to other studies. An interval of corresponding values was found by Söderqvist et al. (2021) to be 160−670 SEK/kg (converted from USD2018 to SEK2021), based on a compilation of results from eight previous valuation studies related to coastal and marine eutrophication effects in the Baltic Sea. The cost in this study is thus within this interval which gives credibility to the result if using this approach. However, the effects of CSOs can be evaluated in alternative ways. Abbasi et al. (2021) evaluate the impacts of CSOs divided into the four criteria of human health, environmental, social, and economic impacts with sub-criteria, e.g. microbiological pathogens, nutrients, changing value of property, and costs of beach closing. Effects related to these criteria could have been included in the case study but many of them are likely to be of minor importance in this context since there is no downstream raw water intake or swimming area. Further, effects of CSOs might also be valued based on the fines which water utilities are obliged to pay because of CSOs. However, it can be discussed if this should be included in a calculation of the cost for society of I/I-water or be a part of other assessments such as a full CBA. The model presented here would serve as one type of basis for a CBA, which would also include measures to reduce I/I-water and associated positive and negative effects. Such a CBA would thus enable a comparison of the costs of such measures with what they would achieve in terms of reduced costs of I/I-water.

The applied system boundary also has a large impact on the results. In the case study, the system boundary represents a broad societal perspective which is recommended when assessing the costs to society due to I/I-water (Ohlin Saletti et al., 2021). However, a narrower system boundary is often used including only internal costs incurred by the water utility or the owner of the WWTP. Applying other system boundaries would result in a different outcome since it determines which effects that are included in the analysis.

Several simplifications were done when applying the method to the case study area which also may have affected the result. One climate factor was used to represent different kinds of changes in flow, i.e. regarding volumes of I/I-water to the WWTP, CSO volumes, and share of basements being flooded. For a more accurate assessment different climate factors can be used for different kinds of phenomena which can affect these factors, e.g. change in precipitation or the groundwater table. Regarding the risk costs, a few rain events with corresponding consequence cost were used and the risk costs were calculated by a simplified approach. A more precise estimation could have been performed by using the events to create a function and using its derivative to estimate the risk cost. Another simplification was done by assuming that the share of flooded houses for rain events with different return periods were the same as for two other areas where hydrological and hydraulic modelling had been performed before. For a more precise result it is suggested to perform area specific modelling.

The choice of using a 100-year time horizon in the case study have also affected the result. This relatively long time horizon was chosen to be able to include investments at the WWTP more distant in the future and since components in the sewer system often are assumed to last for this time period. Some likely changes during the time horizon are acknowledged e.g. by including a climate factor and an increase in treatment cost and cost of CO_2 equivalents. However, all changes in the society that could occur and affect the I/I-water volumes are not accounted for, e.g. related changes in population, land use, and technological development. An evaluation of possible future scenarios was not part of the scope of this paper but this should be investigated further in future research.

With only one case study performed it is difficult to determine whether the results would be similar if applying the model in other areas. If monetising the same effects using similar approaches as done in the case study on areas that have resembling characteristics e.g. in terms of urbanisation level, climate, and dimensioning of the sewer piping system, it is suspected that the outcome would be similar as in the performed case study. However, if changes in the model would be implemented or if the new area differs substantially from the current, the result could turn out very different. Hence, applying the model in alternative ways and at different locations would be interesting in further steps.

5.2. Uncertainty and sensitivity analysis

The sensitivity analysis shows that the choice of discount rate has a large impact on the total *PV* and it should hence be chosen very carefully. In the case study the same discount rate was used for the whole time horizon, however another option would be to use a declining discount rate to account for future uncertainties (Arrow et al., 2014). Moreover, many water utilities lack recommendations on what discount rate to use in analyses related to investments in the water and wastewater system. Such recommendations would be very useful and make it easier to compare results from different studies. Additionally, recommendations are also usually missing regarding risk preference strategies at water utilities, something that has been pointed out by e.g. Sriwastava et al. (2021). In Sweden, there is no general strategy on how to evaluate and treat risks or uncertainties at water utilities. Tools and guidance are provided related to specific topics, but in order to handle risks and to evaluate decision options in a good manner additional recommendations are much needed.

In the sensitivity analyses, the “marginal cost approach” is compared to the “share of cost approach” for calculating the investment costs at the WWTP because of I/I-water. The result shows that the “share of cost approach” results in a much lower cost. The “marginal cost approach” assumes different costs for different flow categories which is appropriate under some conditions, e.g. when performing an assessment in an area that makes out a small share of the total area connected to a WWTP and measures are planned at that location. However, it is not suitable using this approach when calculating the costs of I/I-water for the whole catchment area for a WWTP or if planning to do measures at a larger scale in the system. In those cases, marginal costs are not valid and the “share of cost approach” should be used.

Spearman rank correlation coefficients were used to show which variables that correlate most strongly with the result. The highest and the fifth highest correlated factor was the total volume from the case study area and the total volume to the WWTP. The input data for these variables depend on the precipitation of each modelled year and can therefore vary. The other variables shown to have a large impact on the result are investment cost, share of buildings with basements, share of buildings where basement flooding can occur, uncertainty of share of basement flooding, and cost for treatment. For variables related to where basement flooding can occur the uncertainty could be decreased with more knowledge about the system. However, data about share of basements are often missing and characterising each building can be very resource demanding (e.g., De Angeli et al., 2016).

5.3. Expert elicitation

Expert elicitation turned out to be a valuable, but time demanding, method for obtaining information about the included variables. The used process had a few limitations, one being not always having four experts, as recommended by the SHELF-protocol. Further, it was due to time and budget restrictions not possible to go through all QoIs during the workshops and therefore simplified elicitation or minimal assessment were used for some of the variables. Moreover, the selection of the experts might have affected the result. However, selecting experts with deep individual knowledge that together covered different perspectives of the QoIs as well as being independent from the stakeholders’ subjective position, should have contributed to minimise biases. The main aim of the case study is to illustrate the presented novel model using a real location and the elicitation process was restricted by the project resources. Although the case study shows valuable results, the quantification of the input variables can be expanded. As part of this, more extensive elicitation can be performed in future projects with more resources available.

6. Conclusion

The main conclusions from this study are:

- The presented model provides a novel approach for assessing the costs to society of I/I-water by including internal and external costs as well as uncertainties. Expert elicitation was shown to be a helpful method to quantify input variables.
- The case study application showed that costs due to investments at the wastewater treatment plant and from basement flooding events were dominant. This provides valuable guidance for managing I/I-water in the case study area, but the results are dependent on the applied system boundaries and thus the selected effects of I/I-water included in the case study (treatment of wastewater, pumping, combined sewer overflows, and basement flooding) and the choice of approach for monetisation of these effects. Hence, the selection of effects and choice of monetisation approaches are important steps, especially if different areas are to be compared.
- The model facilitates comparison of costs of I/I water between different study areas, and thus a basis for prioritising cost-reducing measures. The risk-based approach of the model makes it possible to investigate the sensitivity of the selection of discount rate, time horizon, selection of effects, and monetisation approaches with respect to the end result. That, in turn, can contribute to building consensus among the stakeholders on these issues for cost calculations of I/I water, which would be favourable.
- Further research is suggested on how future changes in society affect the result as well as regarding extending the model to perform a full cost-benefit analysis where costs to perform measures to reduce I/I-water are compared to benefits in terms of decreased costs of I/I-water.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A – Notations

Table A1

Table A.1
Notations used in the paper. MU = monetary unit.

Variable	Description and unit
A	number of areas where FRC/SRC is monitored a $(a=1...A)$
$area_a$	area of area a [m^2]
B	number of building types $b(b=1...B)$ with different restoration costs
$C_{rp_{BF}}$	cost of basement flooding events for return period rp [MU]
$C_{rp_{CSO}}$	cost of CSOs for return period rp [MU]
C_t	cost of effects year t [MU]
$c_{BF_{rp}}$	cost of basement flooding events for return period rp_{BF} [MU]
cb_b	cost of a basement flooding for building type b [MU]

(continued on next page)

Table A.1 (*continued*)

Variable	Description and unit
c_{CO2_t}	cost per CO_2-equivalents for year t [MU/CO_2-eq]
c_{FRC}	cost of fast response components reaching the WWTP [MU/m^3]
cf	climate factor expressing change due to climate change during the time horizon T [-]
c_f	cost of investment for flow category f [MU/m^3]
$c_{p_{in}}$	internal cost for pumping I/I-water [MU/kWh]
c_{SRC}	cost of slow response components reaching the WWTP [MU/m^3]
c_{tr}	cost for treatment of I/I-water [MU/m3]
E_{lift}	energy needed to lift the I/I-water to the WWTP [kWh/m^3]
E_p	energy consumption for pumping I/I-water [kWh/m^3]
e_{CO2}	CO_2 equivalents per kWh [CO_2-eq/kWh]
F	number of flow intervals f $(f=1...F)$
FRC_t	share of FRC of I/I-water volume from case area year t [-]
$f_{U_{BF}}$	scaling factor depending on the return period [-]
h_z	number of detached houses in zone z
inc_{tr}	factor expressing how much the cost to treat I/I water is expected to increase in real terms [-]
inv_{disc}	discounted investment cost at WWTP [MU]
inv_t	investment cost at WWTP per year [MU/year]
$M_{rp_{CSO}}$	mass of phosphorus and nitrogen in CSO at return period rp [kg]
N_{PO_4eq}	factor to convert nitrogen to PO_4-equivalents [-]
NB_b	number of buildings of building type b
N_{ss}	concentration of nitrogen in sanitary sewage [kg/m^3]
N_{sw}	concentration of nitrogen in stormwater [kg/m^3]
P_{PO_4eq}	factor to convert phosphorus to PO_4-equivalents [-]
P_{ss}	concentration of phosphorus in sanitary sewage [kg/m^3]
P_{sw}	concentration of phosphorus in stormwater [kg/m^3]
PV	present value [MU]
PV_{CSO}	present value of CSOs due to I/I-water [MU]
$PV_{BF_{in}}$	present value of the inconvenience cost of basement flooding events [MU]
$PV_{P_{env}}$	present value of the environmental cost of pumping I/I-water [MU]
$PV_{P_{in}}$	present value of the internal pumping cost [MU]
$PV_{R_{BF}}$	present value of the restoration cost of basement flooding events [MU]
PV_{WWTP_i}	present value of investment due to I/I-water at WWTP [MU]
$PV_{WWTP_{tr}}$	present value of treatment of I/I-water from case area [MU]
r	social discount rate [-]
R_{BFt}	risk cost of basement flooding event in the case area due to I/I-water year t [MU]
R_{CSOt}	risk cost of CSOs because of I/I-water from case area year t [MU]
RP_{CSO}	the number of return periods used for CSOs rp_{CSO} $(rp_{CSO}=rp_1...RP_{CSO})$
RP_{BF}	the number of return periods used for basement flooding events rp_{BF} $(rp_{BF}=rp_1...RP_{BF})$
SRC_t	share of SRC of I/I-water volume from case area year t [-]
s_{a_f}	share of flow in flow interval $f$reaching the WWTP from area a [-]
s_{base}	share of buildings with basements in the area where basement flooding events can occur [-]
s_{flood}	share of buildings in the case area where basement flooding could occur due to the sewer system [-]
s_{invf}	share of investment cost corresponding to flow category f [-]
s_n	share of achieving good status being fulfilled by reaching target levels of phosphorus and nitrogen [-]
$s_{rp_{BF}}$	the share of basements being flooding during rain with return period rp_{BF} [-]
s_{v_f}	share of volume reaching the WWTP in flow category f [-]
T	time horizon including the years t $(t=0...T)$
t_r	treatment requirement [kg/year]
t_{r_N}	treatment requirement for nitrogen [kg/year]
t_{r_P}	treatment requirement for phosphorus [kg/year]
U_{BF}	scaling factor due to the type of building construction [-]
$V_{I/I}$	total volume of I/I-water from case area over time horizon [m^3]
V_{I/I_t}	volume of I/I-water from case area over year t [m^3]
V_{WWTP}	total volume reaching WWTP over time horizon [m^3]
V_{WWTPt}	volume reaching WWTP year t [m^3]
$V_{ss_{rp_{CSO}}}$	volume sanitary sewage in CSO for return period rp_{cso} [m^3]
$V_{sw_{rp_{CSO}}}$	volume stormwater in CSO for return period rp_{cso} [m^3]
WTP_{BF_z}	WTP per household to avoid basement flooding in zone z [MU/year]
WTP_{gs}	WTP to reach good status in recipients in the City of Gothenburg [MU/year]
yc_{cf}	yearly change due to climate factor [-]
yc_{CO2}	yearly change in cost for CO_2-equivalents [-]
Z	the number of zones z $(z=0...Z)$ for inconvenience of basement flooding events
τ	mass of phosphorus and nitrogen to be removed to reach their corresponding target levels [kg/year]

Appendix B – Input data used in case study

Table B1, Table B2, Fig. B1

Table B.1
Input data case study.

Input	Unit	Abbr.	Point value	Variables	Used distribution	Source
General						
Discount rate	-	*r*	0.035			(Swedish transport administration, 2020)
Climate factor	-	*cf*	1.25			(Swedish Water, 2016)
Time horizon	yrs	*T*	100			
WWTP						
Volume of I/I-water from case area over year *t*	m^3	V_{I/I_t}		1 940 512 / 2 171 696 / 2 441 090	Pearson (Q1/M/Q3)	Hydrological and hydraulic modelling, fitting 18 years data
Cost for treatment of I/I-water	SEK/ m^3	c_{tr}		0.5 / 0.8 / 1.0 / 1.35 / 2.0	Lognormal (L/Q1/M/Q3/U)	Full SHELF-protocol workshop (WS-A)
Increase treatment cost	-	inc_{tr}	1.5			
Investment WWTP year 0-10 [1]	Million SEK	$inv_{0\text{-}10}$		500 / 800 / 1 000 / 1 200 / 1 500	Normal (L/Q1/M/Q3/U)	
Investment WWTP year 11-50 [1]	Million SEK	$inv_{11\text{-}50}$		5 000 / 9 500 / 11 000 / 12 000 / 14 000	Beta (L/Q1/M/Q3/U)	
Investment cost WWTP year 51-100 [1]	Million SEK	$inv_{51\text{-}100}$		5 000 / 10 000 / 12 000 / 16 000 / 22 000	Beta (L/Q1/M/Q3/U)	
Share of investment 0-1.99 m^3/s	-	$s_{inv_{0-2}}$		0.39 / 0.53	Beta (M/Q3)	Email after WS-A – linear pool. Combined with Dirichlet distribution
Share of investment 2-3.99 m^3/s	-	$s_{inv_{2-4}}$		0.19 / 0.30	Beta (M/Q3)	
Share of investment 4-6.66 m^3/s	-	$s_{inv_{4-7}}$		0.22 / 0.32	Beta (M/Q3)	
Share of investment 7-9.99 m^3/s	-	$s_{inv_{7-10}}$		0.09 / 0.14	Beta (M/Q3)	
Share of investment 10-16 m^3/s	-	$s_{inv_{10-16}}$		0.11 / 0.15	Beta (M/Q3)	
Total volume to WWTP per year	m^3	$V_{WWTP\,t}$		128 933 990 / 137 792 219 / 147 480 697	Pearson (Q1/M/Q3)	Hydrological and hydraulic, fitting 18 years data
Share of flow 0-1.99 m^3/s	-	$s_{v_{0-2}}$		0.36 / 0.42 / 0.49 / 0.56	Beta (L/Q1/Q3/U)	Hydrological and hydraulic,, 18 year data, combined with Dirichlet distribution
Share of flow 2-3.99 m^3/s	-	$s_{v_{2-4}}$		0.24 / 0.34 / 0.35 / 0.44	Beta (L/Q1/Q3/U)	
Share of flow 4-6.99 m^3/s	-	$s_{v_{4-7}}$		0.04 / 0.12 / 0.16 / 0.24	Beta (L/Q1/Q3/U)	
Share of flow 7-9.99 m^3/s	-	$s_{v_{7-10}}$		0 / 0.03 / 0.05 / 0.14	Beta (L/Q1/Q3/U)	
Share of flow 10-16 m^3/s	-	$s_{v_{10-16}}$		0 / 0.01 / 0.02 / 0.12	Beta (L/Q1/Q3/U)	
Area of area where FRC / SRC is monitored [2]	m^2	$area_a$				Hydrological and hydraulic,
Share of flow interval from area *a* [2]		s_{a_f}				
Share of SRC from case area per year	m^3	S_{SRC}		0.13 / 0.22 / 0.24 / 0.33	Beta (L/Q1/Q3/U)	Hydrological and hydraulic,, 18 year data, combined with Dirichlet distribution
Share of FRC from case area per year	m^3	S_{FRC}		0.67 / 0.76 / 0.78 / 0.87	Beta (L/Q1/Q3/U)	
Pumping						
Energy consumption financial analysis	kWh/m3	$E_{p_{in}}$		0.1 / 0.12 / 0.13 / 0.14 /0.15	Normal (L/Q1/M/Q3/U)	Minimal assessment (WS-D)
Financial cost pumping I/I-water	SEK/kWh	$c_{p_{in}}$		0.7 / 1.25 / 1.5 / 2.0 / 4	Lognormal (L/Q1/M/Q3/U)	
Energy lift	kWh/m3	E_{lift}	0.065			Calculation, 24 m lift
Cost per CO_2-equivalent year 2021 / year 2031	SEK/CO_2-eq	c_{CO2}	0.80 / 6.31			(EMBER, 2022) / (Isacs et al., 2016), converted to SEK 2021
CO_2-equivalents per kWh	CO_2-eq/ kWh	e_{CO2}		0 / 0.26 / 0.35 / 0.44 / 1	Normal (L/Q1/M/Q3/U)	Minimal assessment (WS-D)
Yearly change in cost of CO2-eq 2021-2030	-	$yc_{CO2\,2021-2030}$		0.17	Uniform	Minimal assessment after WS-D
Yearly change in cost of CO2-eq 2031-2121	-	$yc_{CO2_{2031-2121}}$		-0.02 / 0 / 0.004	Beta pert (L,P50/P90)	
CSO						
WTP recipient	Million SEK/year	WTP_{gs}		50 / 156 / 169,5 / 183 / 300	Normal (L/Q1/M/Q3/U)	Minimal assessment (WS-D)
Share of requirement	-	s_n		0.05 / 0.15 / 0.2 / 0.25 / 0.35	Beta (L/Q1/M/Q3/U)	Full SHELF-protocol workshop (WS-B)
Volume sanitary sewage CSO in CSO for return period 0,02 / 0,08 / 0,5 / 1 / 2 / 5 / 10 / 20 years	m^3	$V_{SS_{rp_{CSO}}}$		155 / 245; 189 / 293; 252 / 383; 282 / 420; 313 / 457; 403 / 574; 493 / 678; 581 / 793;	Uniform (L/U)	Hydrological and hydraulic modelling
	m^3	$V_{SW_{rp_{CSO}}}$		871 / 1 112; 1 452 / 1 815; 3 791 / 4 635; 5 635 / 6 735; 8 127 / 9 491;	Uniform (L/U)	

(*continued on next page*)

Table B.1 (*continued*)

Input	Unit	Abbr.	Point value	Variables	Used distribution	Source
Volume stormwater in CSO for return period 0,02 / 0,08 / 0,5 / 1 / 2 / 5 / 10 / 20 years				13 057 / 14 891; 18 343 / 20 418; 25 392 / 27 569		
Phosphorus in sanitary sewage	kg P/m^3	P_{SS}		2.0 / 4.9 / 6.0 / 7.0 / 9.0	Beta (L/Q1/M/Q3/U)	Email after WS-B – linear pool
Phosphorus in stormwater	kg P/m^3	P_{SW}		0.04 / 0.15 / 0.19 / 0.25 / 0.65	Lognormal (L/Q1/M/Q3/U)	
Nitrogen in sanitary sewage	kg N/m^3	N_{SS}		17.5 / 22.5 / 29.0 / 34.5 / 42.5	Gumbel type II (L/Q1/M/Q3/U)	
Nitrogen in stormwater	kg N/m^3	N_{SW}		0.70 / 1.55 / 1.85 / 2.20 / 4.25	Gamma (L/Q1/M/Q3/U)	
Conversion factor phosphous		P_{PO_4eq}	3.07			As used in Söderqvist et al. (2021)
Conversion factor nitrogen		N_{PO_4eq}	0.42			
Treatment requirement phosphorus	kg P/year	τ_P		1 000 / 3 000 / 4 000 / 5 000 / 6 000	Normal Normal (L/Q1/M/Q3/U)	Full SHELF-protocol workshop (WS-B)
Treatment requirement nitrogen	kg N/year	τ_N		25 000 / 160 000 / 240 000 / 310 000 / 500 000	Weibull (L/Q1/M/Q3/U)	
Basement flooding						
Share of basement flooding events for return period 1/ 2 / 5 / 10 / 20 / 50 / 100 / 200 years, 2121	-	$S_{rp_{BF}}$	0 / 0 / 0.5 / 0.2 / 0.4 / 0.7 / 0.85 / 0.9			Hydrological and hydraulic modelling
Uncertainty distribution share of flooding	-	U_{BF}		0.8 / 0.85 / 0.95 /1	Beta. (P05/P25/P75/P95)	Minimal assessment after WS-D
Factor for uncertainty of share of flooding for return period 1/ 2 / 5 / 10 / 20 / 50 / 100 / 200 years, 2121	-	$f_{U_{BF}}$	0.06 / 0.22 / 0.44 / 0.78 / 0.94 / 1			
Share of buildings where basement flooding can occur	-	s_{flood}		0.55 / 0.70 / 0.78 / 0.83 / 0.95	Beta (L/Q1/M/Q3/U)	Full SHELF-protocol workshop (WS-C)
Share of buildings that have basements	-	s_{base}		0.65 / 0.73 / 0.80 / 0.85 / 0.92	Weibull (L/Q1/M/Q3/U)	
Cost basement flooding detached house	SEK/house	cb_{de}		54 896 / 2609	Lognormal (μ/σ)	(Rosén & Nimmermark, 2018) converted from 2014 to 2021
Cost basement flooding apartment / commercial building	SEK/building	cb_{ap}		221 917 / 17 537	Lognormal (μ/σ)	(Rosén & Nimmermark, 2018) converted from 2014 to 2021
Cost basement flooding public building	SEK/bulding	cb_{pu}		210 238 / 17 771	Lognormal (μ/σ)	
Number of detached houses	-	NB_{de}		396 / 400 / 404	Beta pert (L/M/U)	GIS- system, City of Gothenburg and minimal assessment after WS-C
Number of apartment / commercial buildings	-	NB_{ap}		684 / 760 / 836	Beta pert (L/M/U)	
Number of public buildings	-	NB_{pu}		287 / 290 / 293	Beta pert (L/M/U)	
Number of detached houses in zone 0-99.99/100-1000/1000+ meter from previous basement flooding	-	h_z	73 / 327 / 0			GIS-system, City of Gothenburg
WTP per household in detached houses to avoid flooding 0-99.99m	SEK/year	$WTP_{BF_{0-100}}$		1500 / 2366	Lognormal (μ/σ)	(Torgersen & Navrud, 2018) converted from NOK 2017 to SEK 2021
WTP per household in detached houses to avoid flooding 100-1000m	SEK/year	$WTP_{BF_{100-1000}}$		828 / 1524	Lognormal (μ/σ)	
WTP per household in detached houses to avoid flooding 1000+ m	SEK/year	$WTP_{BF_{1000+}}$		151 / 1351	Lognormal (μ/σ)	

Table B.2
Areas where SRC / FRC is monitored.

	Flow [m^3/s]					Area		Flow [m^3/s]					Area
	0-2	2-4	4-7	7-10	10-			0-2	2-4	4-7	7-10	10-	
SRC 1	0%	25%	44%	18%	13%	665 m^2	FRC1	0%	14%	36%	24%	26%	60 m^2
SRC 2	0%	25%	46%	17%	11%	742 m^2	FRC2	0%	9%	40%	25%	26%	44 m^2
SRC 3	0%	28%	48%	15%	9%	328 m^2	FRC3	0%	9%	38%	23%	31%	58 m^2
SRC 4	0%	28%	47%	16%	9%	176 m^2	FRC4	0%	9%	40%	23%	29%	213 m^2
SRC 5	0%	28%	48%	15%	9%	665 m^2	FRC5	0%	11%	43%	27%	19%	144 m^2
SRC 6	0%	25%	44%	18%	13%	651 m^2	FRC6	0%	20%	36%	21%	23%	50 m^2
SRC 7	0%	22%	45%	20%	13%	390 m^2	FRC7	0%	11%	34%	26%	29%	405 m^2
SRC 8	0%	32%	32%	26%	10%	494 m^2	FRC8	0%	15%	46%	20%	18%	95 m^2
SRC 9	0%	26%	45%	18%	11%	500 m^2	FRC9	0%	9%	39%	28%	24%	158 m^2
SRC 10	0%	36%	41%	15%	8%	2682 m^2	FRC10	0%	13%	46%	22%	19%	220 m^2
SRC 11	0%	23%	46%	19%	12%	559 m^2	FRC11	0%	8%	35%	28%	29%	88 m^2
SRC12	0%	28%	48%	15%	9%	761 m^2							

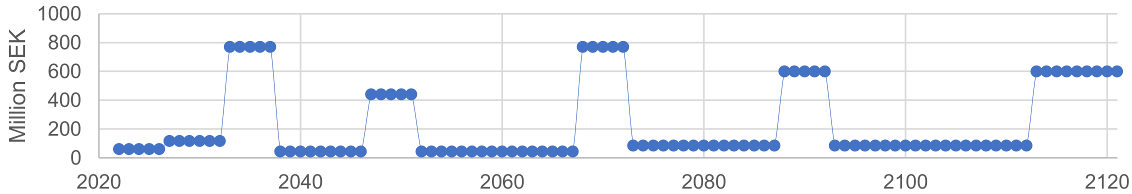

Fig. B1. Estimation of yearly distribution of investment costs at the WWTP.

Appendix C – Input data used in sensitivity analyses

The data used in the sensitivity analyses is presented in Table C.1.

Table C.1
Data used in sensitivity analyses.

	Variables in base analysis	Variables in sensitivity analysis	Comment
Discount rate (*r*)	0.035	0.0015 / 0.06	Recommended by Johansson and Kriström (2016)
Climate factor (*cf*)	1.25	1.1 / 1.4	(Svensson et al., 2020)
Investment WWTP	See equation 10–14 (marginal cost approach)	See equation 15 (share of cost approach)	
Inconvenience basement flooding 0-100/ 100–1000/1000 meter			Number of buildings calculated using the same proportions in the zones as for small houses. Inconvenience cost per building calculated using the same proportions as for the restoration costs.
Detached houses	Number of buildings: 73/327/ 0 Cost per buildings: 1500/828/ 151	Number of buildings: 73/327/0 Cost per buildings: 1500/828/151	
Apartment/ commercial buildings	-	Number of buildings: 139/621/0 Cost per buildings: 6063/3348/609	
Public buildings	-	Number of buildings: 53/237/0 Cost per buildings: 5743/3172/577	

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