

3. Optimisation tool

3.1. AIM OF THE TOOL

The optimization tool consists of a mathematical model formulation and a software implementation of that model. The model is an abstraction of real-life situations and is intentionally held rather simple to provide a quick overview, scouting out suitable and good solutions. It is intended to serve as a screening tool, e.g., early on in decision processes before the suggested solutions will be analysed and designed in more detail with dedicated tools such as SWMM or MAR/SAT.

The aim of the optimization tool is to find suggestions for combinations of (nature-based) solutions for stormwater management across a site such as a catchment. These suggestions comprise the type and area share of the single solutions at given locations on the studied site. The suggested combinations are chosen with the aim to minimize costs and, in some cases, also discharge from the site. For this, the model takes into account (simplified) descriptions of the hydrology at the site and hydrologic properties of the explored stormwater management solutions, area restrictions at the single locations and restrictions on the discharge (run-off) from the site at a discharge point.

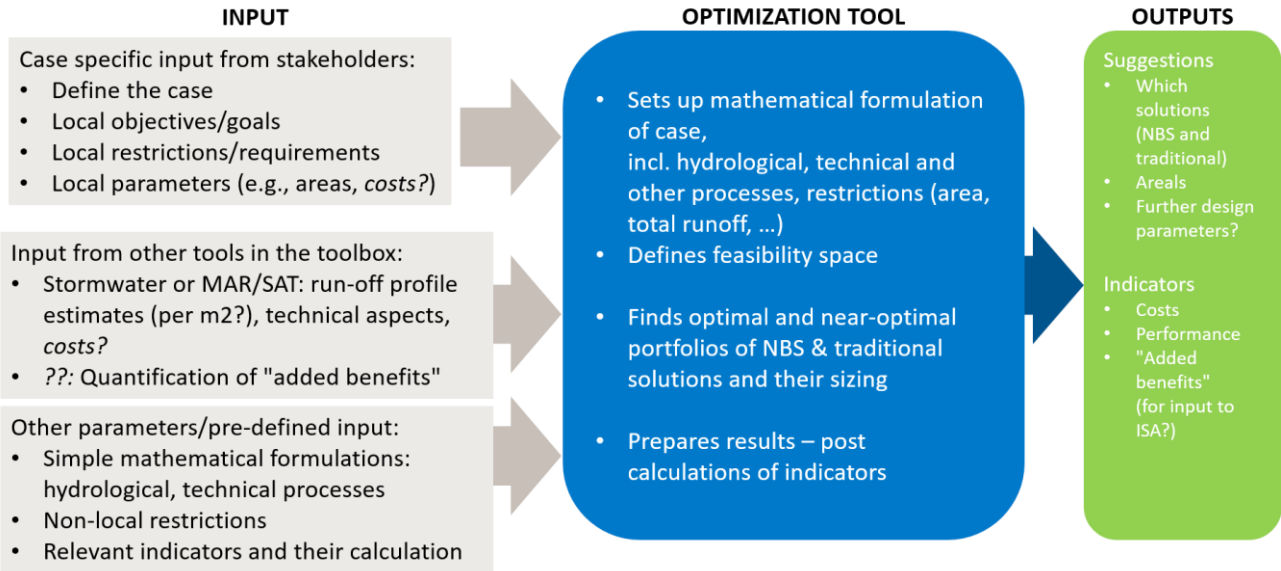


Figure 1: Input information and results from the optimization tool

During the EviBAN project, the optimization tool has been developed based on a study case in Trondheim/Norway. This case studied a site on the university campus and was concerned with the question: What is the optimal combination of stormwater measures on the new campus site to meet both regulations for discharge of stormwater into the municipal infrastructure and to reduce the risk for flooding of the newly erected ZEB Lab downstream of the site? The tool has been tested on a similar case in the Vallikallio area of Espoo/Finland. This case explored also the interplay with the SWMM tool in an interactive manner to find technical specifications of the NBS (section 3.2.3) and thus to calibrate the tool input. A somewhat different potential application of the tool is a study case in Riversdale/South Africa. Here, nature-based solutions should be found to augment water supply/storage and mitigate water shortages.

3.2. MODELLING DETAILS

3.2.1. Simplified run-off modelling – a network of nodes

To model hydrology of a considered catchment, advanced models exist (e.g., SWMM), taking into account, e.g., drainage lines, infiltration properties, (variation of) saturation over the considered catchment area, location, and connections between different NBS.

Alternatively, a simplified run-off modelling based on nodes may be used:

We discretize the whole considered area into a number of *nodes*, which represent typical points in the catchment area. One kind of nodes is places where traditional or nature-based water-management solutions may be installed or do exist. Another kind is places that are remarkable from a run-off point of view. The selection of nodes should be such that it covers the most important features of the considered case.

For each node, a surrounding area¹ is determined and the neighbour nodes to which storm water may drain to. Also, the time it takes for water to drain from one node to another, the time of concentration, is defined. This may be done using more complex technical models.

The outlet or sink node (node 0) is a special kind of node.² It collects all volumes flowing out of the system. We assume that at this node no NBS or traditional solutions can be installed. Hence, the area assigned to the node is set to zero. This means also that no rain fall is taken into account for that node. Consequently, the outflow at this node in a given time period equals the inflow in this time period. In addition, there may be an upper limit on this water volume – such a limit is not present at the other nodes in the network.



Figure 2: Example: Discretization of a catchment area into a network of nodes

In the example illustrated in Figure 2, storm water management solutions can be installed in nodes 5, 6, 9 and 10. Nodes 1, 2, 3, 4, 7 and 8 only collect the water to send it further and no water management solutions are considered there. Node 0 is the sink node where all water eventually drains to, to be measured against a critical run-off limit. Numbers in parentheses along the connections between the nodes signify time of concentration (in time periods).

¹ The sum over all node areas should correspond to the total or relevant area of the considered catchment.

² As a future extension of the model, several (separate) sink nodes may be considered.

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In EviBAN SWMM has been used for stormwater modelling, while a node model has been used for MAR

3.2.2. Hyetographs

The hydrological model input specifies some profiles for rainfall events (hyetographs) that may be typical or interesting for the case to be analysed. Hyetographs are typically given in input files, so it is possible to easily change the selected profile and re-run the model, analysing the suggested solutions with respect to robustness or flexibility. A hyetograph may denote a single event but also a combination of consecutive events. The hyetographs are given in the form of a series of values, stating the volume of rainwater falling on an area of a standard size (e.g., in l/m²) during a given time interval (e.g., 10 minutes). These values may be constructed, for example, based on observed intensity-duration-frequency curves for a chosen return period.

Typically, the profiles are stated only for the duration of the rain event, e.g., over one hour (6 periods of 10 minutes each). The model's time horizon, however, is assumed to be much longer to account for the longest duration the water will stay in the system – considering the water's travel from the first node through the system down to the sink node. This takes also into account the time it takes to pass the various measures in the nodes and the time of concentration between the nodes.³

3.2.3. Technical modelling of water management measures

The technical properties of the water management measure (both the NBS and the traditional approach) are modelled in a simplified way using two basic aspects, loss (e.g., through evaporation or infiltration) and retention (delayed release). Both are expressed as a percentage of the volume of water entering the measure in a node during a given time period:

For the node model, we assume that a rain event happens right at the start of the horizon. Consequently, the length of the hyetograph is adjusted to the length of the model horizon. We assume also that the same hyetograph applies to all nodes (however, this assumption is not critical).

First, the amount of water entering the measure in a node in a time period is determined using the area share of the measure in the node: If a measure occupies x % of the total area available in the node, then x % of the total water entering the node at the time period are assumed to enter this measure.

Then, we estimate how much of that volume evaporates or is infiltrated in the measure – i.e., is lost from the system – during this time period, e.g., 5 %. Finally, we assume that the remainder of the water will be released gradually from the measure, i.e., distributed over the following time periods according to a retention profile given in percent of this remainder. For example, 10 % may be released in the subsequent time period, 40 % in the next one, 40 % in the next one again, and the remaining 10 % in the fourth time period after entering the measure, see Figure 3.

³ This is not a strict requirement, however, as the most important time periods are those where high flow volumes are to be expected. Our focus is on dimensioning the NBS portfolio to tackle flow peaks, and the later time periods with the last remainders of the stormwater event trickling through the system are not relevant.

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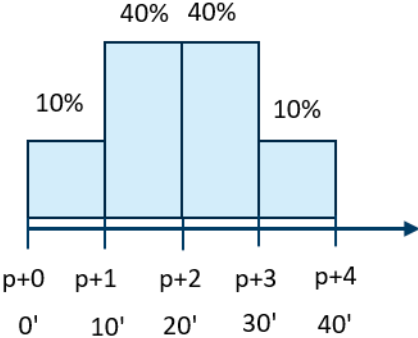


Figure 3: Example: Retention profile of an NBS

To determine the aggregated amount of water released from a measure during a time period, we sum up over the shares of water that entered the measure earlier that will be released at the considered time periods. Consider, for example, a time horizon $p, \dots, p + 6$ and a water management measure with a retention profile as described above (see Figure 4):

At the end of the first time period ($p + 1$), a certain volume V_1 (e.g., rain water and water released from other nodes) has arrived at the NBS of which 5 % are lost. Hence, 95 % of V_1 (say, V_1^N) actually enter the measure. No water is released from the solution yet.

At the end of the next time period, 10 % of V_1^N will be released from the measure. Also, a new volume V_2 arrived at the solution – also here, 5 % are lost, and 95 % (V_2^N) actually enter the measure.

At the end of the third time period, 40 % of V_1^N are released. Also, water from V_2^N will be released, 10 %.

At the end of the fourth time period, 40 % of V_1^N and 40 % of V_2^N are released.

At the end of the fifth period, the remaining 10 % of V_1^N are released and 40 % of V_2^N .

Finally, at the end of the sixth time period $p + 6$, the remainder of V_2^N is released.

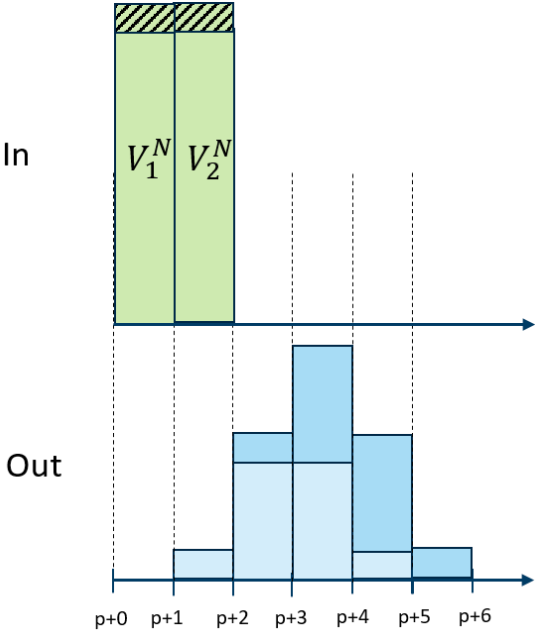


Figure 4: Example: Illustration of water-management properties of an NBS. Of the volumes entering the NBS during two consecutive time periods (green boxes), a certain percentage is lost (green/black-hatched boxes) while the remainder is gradually released through the NBS (light and darker blue boxes).

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The total loss in a node at a given time period is then the sum over all losses in all measures installed in the node. Likewise, the total volume of water leaving the node in a time period is the sum over all volumes released from the single measures during that time period.

Note that this simplified modelling does not take into account changes of infiltration/evaporation and release properties due to, e.g., saturation of the NBS over time.

3.3. SETS AND INPUT PARAMETERS

$\mathcal{N} = \{0, \dots, N\}$	Nodes; $n = 0$ denotes the sink node
$\mathcal{S} = \{0, \dots, S\}$	(Nature-based) solutions; $s = 0$ denotes the traditional/do-nothing measure
$\mathcal{T} = \{1, \dots, T\}$	Time units / periods for rain water flow modelling (e.g., 10 min intervals)
$\mathcal{T}^E = \{1, \dots, T^E\}$	Time units / periods for economics modelling (e.g., years)
$\mathcal{T}^D = \{1, \dots, T^D\}$	Time units / periods for detention flow profile modelling

(Same length as or a multiple of $t \in \mathcal{T}$, e.g., 10 minutes)

Note: In principle, T should be "sufficiently large" such that all water flowing to the sink node can be accounted for. Currently, it is set manually as it is not a priority in the model development.⁴ Also, of interest for dimensioning a good selection of NBS are the *first* time periods when water volumes into the sink reach their peak and having a good value for T is not that important for the results.

<i>CostLimit</i>	€	Limit on total costs over optimization horizon
<i>DiscountFactor_t</i>		Discount factor in time unit (year) $t \in \mathcal{T}^E$
<i>DiscountRate</i>	$\in [0,1]$	Discount rate $DiscountFactor_t = 1/(1 + DiscountRate)^{t-1}$
<i>InfRate_s</i>	$\in [0,1]$	Infiltration rate of solution $s \in \mathcal{S}$ (loss)
<i>InvCost_s</i>	€/m ²	Investment costs per square meter of solution $s \in \mathcal{S}$ installed
<i>LinkShare_{n,nn}</i>	$\in [0,1]$	Share of flow out of node $n \in \mathcal{N}$ going into node $nn \in \mathcal{N}$
<i>LinkTime_{n,nn}</i>		Time for flow from node $n \in \mathcal{N}$ to travel to node $nn \in \mathcal{N}$ (in whole time units/periods)
<i>Loss_s</i>	$\in [0,1]$	Total evaporation or infiltration loss in solution $s \in \mathcal{S}$
<i>MaintCost_s</i>	€/m ²	Yearly maintenance costs per square meter of solution $s \in \mathcal{S}$ installed
<i>NBSLimit_n</i>	m ²	Limit on total area of NBS installed in a node $n \in \mathcal{N}$
<i>NodeAreal_n</i>	m ²	Area in node $n \in \mathcal{N}$ available for (nature-based) solutions
<i>NodeSol_{n,s}</i>	$\in \{0,1\}$	Possible to install solution $s \in \mathcal{S}$ in node $n \in \mathcal{N}$? (no/yes)
<i>RainProfile_{n,t}</i>	l/m ²	Rainfall volume falling in node $n \in \mathcal{N}$ during time period $t \in \mathcal{T}$ (forming a profile)

⁴ A good value for T to take into account all volumes may also be determined automatically based on the concentration time $LinkTime_{n,nn}$ between the single nodes and the retention profiles $RetentionProf_{s,t}$ of the measures. For example, one may determine the longest path through the network of nodes and its length (using $LinkTime_{n,nn}$) and add the duration of the rainfall event and the sum of the longest retention profiles of the feasible measures in each node along this path.

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$RetentionProf_{s,t}$ (forming a profile)	$\in [0,1]$	Retention of solution $s \in \mathcal{S}$ during time period $t \in \mathcal{T}^D$
$SinkLimit$ $t \in \mathcal{T}$	m^3	Upper limit for flow fed into sink node during any time period

3.4. MODEL VARIABLES

$shareSol_{s,n}$ installing solution $s \in \mathcal{S}$ (decision variable)	$\in [0,1]$	Share/percentage of available area in node $n \in \mathcal{N}$ used for
$costNode_n$ \mathcal{N}	Kr	Total costs of installing (nature-based) solutions in node $n \in \mathcal{N}$
$costSol_s$ nodes	Kr	Total costs of installing (nature-based) solution $s \in \mathcal{S}$ in all
$inNode_{n,t}$ \mathcal{T}	m^3	Volume of water entering node $n \in \mathcal{N}$ during time period $t \in \mathcal{T}$
$inNodeSol_{s,n,t}$ \mathcal{N} during time period $t \in \mathcal{T}$	m^3	Volume of water to be handled by solution $s \in \mathcal{S}$ in node $n \in \mathcal{N}$
$qLoss_n$	m^3	Total loss of water that entered node $n \in \mathcal{N}$
$outNode_{n,t}$ time period $t \in \mathcal{T}$	m^3	Volume of water leaving node $n \in \mathcal{N}$ to other nodes during
$outNodeSol_{s,n,t}$ nodes during time period $t \in \mathcal{T}$	m^3	Volume of water leaving solution $s \in \mathcal{S}$ in node $n \in \mathcal{N}$ to other

3.5. CONSTRAINTS

3.5.1. Hydrology:

The water inflow in a node $n \in \mathcal{N} \setminus \{0\}$ during a time period $t \in \mathcal{T}$ consists of rain fall and of water coming in from other nodes, taking into account the time of concentration.

$$inNode_{n,t} = RainProfile_{n,t}NodeAreal + \sum_{\substack{nn \in \mathcal{N}: \\ LinkTime_{nn,n} < t}} LinkShare_{nn,n} outNode_{nn,t-LinkTime_{nn,n}} \quad (1)$$

The inflow meant for retention is divided over the single solutions $s \in \mathcal{S}$ that may exist in that node according to their area share, taking into account the solution's evaporation or infiltration ability $Loss_s$.

$$inNodeSol_{s,n,t} = shareSol_{s,n} inNode_{n,t} (1 - Loss_s) \quad (2)$$

For "bookkeeping", $qLoss_n$ denotes the total water loss through evaporation, infiltration, or the like in node $n \in \mathcal{N} \setminus \{0\}$ over the whole considered time span \mathcal{T} .

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$$qLoss_n = \sum_{\substack{s \in \mathcal{S} \\ t \in \mathcal{T}}} shareSol_{s,n} inNode_{n,t} Loss_s \quad (3)$$

Note that constraints (2) and (3) are nonlinear.

The volume of the flow out of a solution $s \in \mathcal{S}$ installed in a node $n \in \mathcal{N} \setminus \{0\}$, $outNodeSol_{s,n,t}$, to other nodes depends on the retention capacity of that solution, $RetentionProf_{s,t}$. This is described through a profile stating how much of a flow that entered the solution at a given time leaves it after $t \in \mathcal{T}^D$ time periods.

$$outNodeSol_{s,n,t} = \sum_{\tau \in \mathcal{T}^D} inNodeSol_{s,n,t-\tau} RetentionProf_{s,\tau} \quad (4)$$

The total volume $outNode_{n,t}$ of water leaving node $n \in \mathcal{N} \setminus \{0\}$ to other nodes during time period $t \in \mathcal{T}$ is the sum of the volumes leaving the single solutions in the node.

$$outNode_{n,t} = \sum_{s \in \mathcal{S}} outNodeSol_{s,n,t} \quad (5)$$

The critical run-off node or sink node, $n = 0$, only collects the flow from other connected nodes, and no rainfall event or effects of (nature-based) solutions are taken into account. This node represents the discharge from the water system.

$$inNode_{0,t} = \sum_{\substack{nn \in \mathcal{N}: \\ LinkTime_{nn,0} < t}} LinkShare_{nn,0} outNode_{nn,t-LinkTime_{nn,0}} \quad (6)$$

There may an upper limit on the discharge from the sink node (which equals the water inflow into that node) during each time period $t \in \mathcal{T}$.

$$inNode_{0,t} \leq SinkLimit \quad (7)$$

3.5.2. Technical aspects

A solution $s \in \mathcal{S}$ can be installed at a node $n \in \mathcal{N} \setminus \{0\}$ only if this is feasible for technical or other reasons.

$$shareSol_{s,n} \leq NodeSol_{s,n} \quad (8)$$

The totally available area in a node $n \in \mathcal{N} \setminus \{0\}$ cannot be exceeded by the sum of the single areas of all solutions installed at that node.

$$\sum_{s \in \mathcal{S}} shareSol_{s,n} \leq 1 \quad (9)$$

These constraints ensure that the area share of a solution would not exceed 100 %.

There may also be restrictions $SolArealLimit_{s,n}$ on the area available for an installed solution $s \in \mathcal{S}$ in a node $n \in \mathcal{N} \setminus \{0\}$.

$$shareSol_{s,n} NodeAreal_n \leq SolArealLimit_{s,n} \quad (10)$$

Likewise, there may be a restriction $NBSLimit_n$ on the total area of NBS installed in a node.

$$\sum_{s \in \mathcal{S} \setminus \{0\}} shareSol_{s,n} NodeAreal_n \leq NBSLimit_n \quad (11)$$

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3.5.3. Economics

The total costs of solution $s \in \mathcal{S}$ depend on the area used for that solution in all nodes $n \in \mathcal{N} \setminus \{0\}$ and consist of installation and maintenance costs. Simplifying, we assume that maintenance costs per square meter remain constant throughout the optimization horizon.

$$costSol_s = \left(InvCost_s + MaintCost_s \sum_{t \in \mathcal{T}^E} DiscountFactor_t \right) \sum_{n \in \mathcal{N} \setminus \{0\}} shareSol_{s,n} NodeAreal_n \quad (12)$$

Similarly, the costs connected with a node $n \in \mathcal{N} \setminus \{0\}$ depend on the area of each solution $s \in \mathcal{S}$ that is installed in that node.

$$costNode_n = \sum_{s \in \mathcal{S}} \left(InvCost_s + MaintCost_s \sum_{t \in \mathcal{T}^E} DiscountFactor_t \right) shareSol_{s,n} NodeAreal_n \quad (13)$$

There may also be an upper limit on the total costs for installing and maintaining the water management solutions.

$$\sum_{s \in \mathcal{S}} costSol_s \leq CostLimit \quad (14)$$

3.5.4. Objective

The goal of the optimization model is to find a configuration of solutions $s \in \mathcal{S}$ (installed area) in all nodes $n \in \mathcal{N} \setminus \{0\}$ such that the discharge limit (7) is satisfied at lowest possible costs.

$$\min_{shareSol_{s,n}} \sum_{s \in \mathcal{S}} costSol_s = \min_{shareSol_{s,n}} \sum_{n \in \mathcal{N} \setminus \{0\}} costNode_n \quad (15)$$

Alternatively, the goal may be to minimize the total discharge from the system while having an upper limit on the total costs incurred, constraint (14).

$$\min_{shareSol_{s,n}} \sum_{t \in \mathcal{T}} inNode_{0,t} \quad (16)$$

3.6. IMPLEMENTATION

The optimization problem contains some equations describing the water flow that are nonlinear and cannot be linearized easily. Collapsing these equations into one or very few expression(s) would introduce even more nonlinearities due to the recursive character of the model. Hence, the chosen approach is to use Excel as instrument for organizing input and output and a Python script for setting up, instantiating, and solving the optimization model. The optimization model has been implemented in [Python](#) using the [Pyomo](#) optimization package. The model contains nonlinear equality constraints, and the nonlinear solver [ipopt](#) was chosen for the current implementation. However, other nonlinear solvers may also work.

3.6.1. Running the tool

In order to carry out an analysis using the optimization tool, a Python environment is required. To run the tool in *optimization* mode using, e.g., the *ipopt* solver, the following additional steps need to be taken:

- download a release of the solver into the same directory as the Python code or
- specify where the solver is to be found – hard coded – in the Python code (variable *ipopt_exe*) or
- specify where the solver is to be found in the search path.

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Running the tool in *simulation* mode, a Python environment is sufficient, and no solver needs to be installed.

In addition to the *Python code (script)* of the model (see section 3.6.3), a *MS Excel file* organizing the *input data* as described in section 3.6.2 is needed. Currently, the Python script is executed separately ("manually") and the name (and, if needed, the path) of the input MS Excel file is hard coded in the Python script (parameter **ExcellnOrig**). If this input file is open when the script is executed, a temporary copy is created from which the data is read in. This copy is deleted as soon as all data are read. The results of the analysis are written out to an *output MS Excel file* as described in section 3.6.4. If a file with the specified name already exists, it should be closed before executing the Python script.

3.6.2. Input Excel file

The Excel file serving as input for the optimization model consists of seven different worksheets.

Setup

This is an explanatory worksheet with some information about the considered case and which parameters are expected. No information is read from this worksheet.

General data

The worksheet contains a list of parameters controlling the setup of the optimization model:

Discount rate: a value between 0 and 1 (corresponding to 100 %) – a typical value would be 0,07, corresponding to 7%. Read in as parameter *DiscountRate*.

Time units economic modelling (years): optimization horizon for accounting of the investment/installation and maintenance costs of the water management solutions. Read in as parameter T^E .

Time units water modelling: modelling horizon for water management, measured, e.g., as a number of 10-minute intervals. This number should be large enough to allow all rainwater that does not evaporate within the system to reach the sink node (see also comment in section 3.3). Read in as parameter T .

Selected rainfall profile: ID number of the hyetograph selected from worksheet **Design rainfall**.

Run as simulation: any non-zero value indicates that the model is run as simulation with given shares for the measures in each node. These shares are read in from the worksheet **Fixed Shares**.

Optimize discharge: any non-zero value indicates that – instead of the default objective of cost minimization – the discharge is minimized.

Limit on discharge from sink node: limit on volume entering the sink node during any given time period. Read in as parameter *SinkLimit*. (Relevant if optimization considers costs minimization.)

Limit on total costs: limit on total costs incurred. Read in as parameter *CostLimit*. (Relevant if optimization considers discharge minimization.)

Limits on installed measure area in nodes: any non-zero value indicates that there may be individual limits on the area available for each measure in each node. These limits are read in from the worksheet **Nodes**.

Output file name: state name of the Excel file where model output is written to (without ".xlsx" suffix).

Measures

The worksheet describes all rain water management solutions that may be installed in the system. For each measure, it contains information on:

name of the measure,

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an ID number ($s \in \mathcal{S}$),

costs (installation and maintenance costs, $InvCost_s$ and $MaintCost_s$),

evaporation or infiltration ability – loss – (value between 0 and 1), $InfRate_s$

retention profile $RetentionProf_{s,t}$ (described through values for a given number of time steps, stating the share of water entering the measure at time p that leaves it at step pp (i.e., in time period $p + pp$), see also explanation in section 3.3.

Nodes

The worksheet describes details of all nodes in the network. For each node, it contains information on:

an ID number ($n \in \mathcal{N}$),

the total area available for installing water management solutions (e.g., in m^2), $NodeArea_n$,

indication whether there is rainfall (according to the chosen hyetograph) considered in the node,

indication about a possible upper limit on installed NBS area, $NBSLimit$,

indication which measures are suitable to be installed in this node (0... not suitable), $NodeSol_{s,n}$.

If the user indicated in worksheet **General data** that there may be individual limits on the area available for some measures in some nodes, the values given here are interpreted as these area limits (e.g., in m^2), see example in Figure 5. Else, any value larger than zero indicates that the concerned measure is feasible to be installed in the concerned node, with area up to the total area $NodeArea_n$ available in the node.

Nodes	Rainfall		Measures feasible mID (yes>0, no=0)							
ID	Area (m^2)	(yes = 1, no = 0)	All NBS	0	1	2	3	4	5	
0	0	0	0	0	0	0	0	0	0	
1	150	1	125	100	75	50	0	0	50	
2	100	1	100	100	100	100	100	0	100	
3	150	1	150	150	0	150	150	150	0	
4	150	0	120	150	0	150	150	100	100	

Figure 5: Example: Node description. Node 1 has a total area of 150 m^2 available for installation of stormwater management solutions. However, NBS 1 can be installed on only up to 75 m^2 in that node and NBS 2 and 5 on only up to 50 m^2 . NBS 3 and 4 cannot be installed in this node. In total, up to 125 m^2 of NBS can be installed in node 1. No rainfall is considered in nodes 3 and 4.

Network

The worksheet describes the network of nodes, i.e., details of the water flow between the nodes (Figure 6). For each pair of nodes with water flow between them (from node nn to node n) it contains information on:

the share of the flow out of node nn that flows to node n , $LinkShare_{nn,n}$, the time of concentration (number of time periods it takes for water from node nn to reach node n), $LinkTime_{nn,n}$.

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Network				
From node	To node	Amount	Time of concentration	
1	2	0,4	1	
1	3	0,4	1	
1	4	0,2	2	
2	4	1	1	
3	4	0,5	1	
3	0	0,5	1	
4	0	1	1	

Figure 6: Example: Network of nodes with distribution of flow to neighbour nodes and time of concentration

Design rainfall

The worksheet describes a number of rainfall events in the form of profiles (hyetographs) that may be chosen for the optimization model. Each profile ($RainProfile_t$) gives, for a number of time steps (e.g., 10-minute intervals), the volume rain per square meter falling during that interval. At present, we assume that the same profile is valid for all nodes where rainfall is considered.

Fixed Shares

The worksheet describes predefined shares (percentages) of all measures $s \in \mathcal{S}$ in all nodes $n \in \mathcal{N}$, $shareSol_{s,n}$ in the form of values between 0 and 1. For each node, these shares should sum up to 1. This sheet is used as input when the model is run in simulation mode, i.e., with given share values.

3.6.3. Python implementation

The Python implementation of the model consists of two main parts: At first, the model is run with the option of installing NBSs. Depending on the user choice, this happens either as optimization (where the composition of the NBS at each node is chosen freely in order to optimize a given objective) or as simulation using a given composition. Second, a benchmark model is run where no NBS are considered, i.e., all NBS shares are fixed to zero and the non-NBS shares in all nodes are set to one. Also, this is run as a simulation.

The model implementation has the following structure.

1. Read in parameter values from the input file, define sets and adapt the parameter values to the model and implementation requirements. For example,
 - a. Adapt and extend the selected hyetograph to the whole modelling horizon and to all nodes in the network where the rainfall event is considered. This ensures that the same hyetograph is valid in all nodes.
 - b. Equations (8) and (10) are implemented as *limits* on the share, and the table in the **Nodes** worksheet is interpreted slightly differently: If there are individual area limits on measures in the nodes (see section 3.6.2, paragraph on **Nodes**), then the read-in values are recalculated such that they denote limits on the shares of the measures. This is done by dividing the given area limits by the total area of the concerned node. Else, all values larger than zero are interpreted as 1, the maximum possible share.
 - c. Calculate discount factors for all years in the optimization horizon.
2. If the user choice on worksheet General indicates that the model should be run as *optimization*:

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- a. Define expressions for all constraints and the objective function as described in section 3.5.
 - b. Create an instance of the optimization model by activating all required constraints and objective function according to the user choices and populating them with the read-in parameter values.
 - c. Run and solve the instance of the optimization model, find the optimal area shares for all measures in all nodes.
3. Otherwise, run the model as *simulation*:
- a. Fix all decision variables $shareSol_{s,n}$ to the values pre-specified in worksheet **Fixed Shares**.
 - b. Calculate expressions and variables using the equality constraints described in section 3.5.
4. Read out selected model variables for output to the specified Excel file.
5. As a benchmark, create a model instance that considers only the traditional (not nature-based) solution (measure "0"): Set the shares for this solution to 1.
6. Calculate expressions and variables using the equality constraints described in section 3.5.
7. Read out selected model variables for output to the specified Excel file.
8. Construct graphs and plot them, save as .png files.
9. Write the selected output and graphs to the specified output Excel file as described in section 3.6.4. If this file does not exist yet, it is created. Else, all possibly existing values in the file are overwritten.

3.6.4. Output Excel file

The Python script writes selected results from the optimization to an Excel file as specified in the input file.

The file consists of the following worksheets.

General

The worksheet states total costs $\sum_{s \in \mathcal{S}} costSol_s$, the total amount $\sum_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} RainProfile_{n,t} NodeAreal_n$

of rain entering the system and the total amount $\sum_{t \in \mathcal{T}} inNode_{0,t}$ of stormwater entering the sink node throughout the considered time horizon. It also gives information on the percentage of the total rain volume that is discharged and on the volume that was "lost" due to evaporation/infiltration in the nodes. Finally, information is given whether the results have been obtained via simulation or optimization⁵ – for both the case with NBS and the case without NBS.

Shares

The worksheet states the shares $shareSol_{s,n}$ of each measure $s \in \mathcal{S}$ in each node $n \in \mathcal{N}$, (i.e., the decision variables in the optimization model) that are found to be optimal. If the model is run in simulation mode, this should correspond to the values pre-defined in the input file (sheet **Fixed Shares**). Measures are given in columns while nodes are given row-wise. Figure 7 shows an example.

⁵ Then, the objective (minimization of costs or of discharge) and the solver status (e.g., "optimal" or "infeasible") are given.

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	0	1	2	3	4	5	
0	0	0	0	0	0	0	
1	1	2E-08	0	0	0	0	
2	1	2E-08	6,41E-12	0	0	0	
3	1	2E-08	8,25E-13	0	0	0	
4	1	2E-08	2,49E-11	0	0	0	
5	0,380438	0	0,619562	0	0	0	
6	0,270156	0	0,729844	0	3,16E-13	3,16E-13	
7	1	6,52E-14	7,56E-13	0	0	0	

Figure 7: Example: Model output - area shares of each measure in each node. Here, the optimal solution is to use 62% of the available area in node 5 and 73% of the area in node 6 to install NBS 2 while traditional measures for stormwater management are used on all remaining areas.

Nodes_inflow

The worksheet states the volume $inNode_{n,t}$ of water entering each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows).

Nodes_outflow

The worksheet states the volume $outNode_{n,t}$ of water leaving each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows).

Rain in Nodes

The worksheet states the total volume of rain falling in each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows), taking into account the area of the node.

Loss in Nodes

The worksheet states the loss due to evaporation, infiltration etc. in each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows).

Nodes_inflow_noNBS

The worksheet states the volume $inNode_{n,t}$ of water entering each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows) for the benchmark case where no NBS are installed ($shareSol_{0,n} = 1$).

Nodes_outflow_noNBS

The worksheet states the volume $outNode_{n,t}$ of water leaving each node $n \in \mathcal{N}$ (columns) during each time period $t \in \mathcal{T}$ (rows) for the benchmark case where no NBS are installed ($shareSol_{0,n} = 1$).

Graphs

The worksheet shows some graphical presentation of the model results, exemplified in Figure 8. Currently, this is a) the discharge of rain water through the sink node for the cases with and without NBS and b) the total rainwater amount entering the system and the discharge when NBS are installed. In both graphs, also the discharge limit is indicated.

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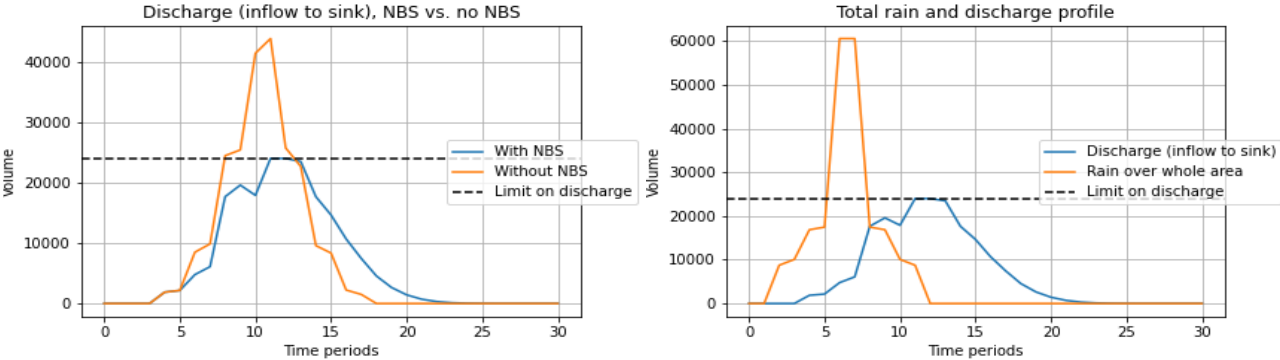


Figure 8: Examples of graphical result presentation.