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Survey of urban drainage efficiency for resilience of groundwater quality

Concept for assessing urban water mass surpluses and deficits and contaminants transport to set climate resilient drainage and infiltration targets

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INTRODUCTION

The quality of groundwater is one of the most important components of a city's functionality. It is crucial for maintaining the entire ecosystem and for all other possible uses of water, especially if it is used for drinking water supply.

A city area, its core and its hinterland, is functional if provide sufficient quantity and quality of water for the ecosystem and for as many uses as possible. A functional urban area is large enough that the annual amount of precipitation can replenish the ecosystem and water supply, while also sufficiently diluting discharges so that there are no detectable concentrations of hazardous substances in the water and no increasing environmental, i. e. spatial or temporal trends of other pollutants.

Urban drainage management and groundwater quality protection share an important management issue: infiltration. Natural infiltration not only helps reduce the burden on sewer systems, but also plays a key role in groundwater replenishment and maintaining hydrological balance.

Modern cities face water surpluses or deficits due to increasing urbanisation, overloaded sewer systems, and significant climate change. Excessive rainfall during storms overloads sewer systems, increasing the risk of untreated wastewater spills and pollution of surface and groundwater. Prolonged dry and wet periods reduce the natural ability to replenish groundwater reserves in aquifers.

Climate change brings additional uncertainty, as we must expect even more frequent and intense rainfall events and longer droughts. This will affect not only the quality and quantity of groundwater resources, but also the operation of sewer networks, which will find it even harder to cope with increased loads.

Therefore, possible solutions are being discussed, such as the introduction of rainwater infiltration systems, retention of water in urban environments, and the promotion of the natural hydrological cycle. These measures require coordinated action by various stakeholders, including city authorities, water management experts, urban planners, and local communities. It is important to identify, monitor, and predict the locations and main causes of overloads, i.e., surpluses of pollutants and water mass surpluses and deficits. On this basis, it is possible to assess how much the performance of the stormwater drainage system would be improved by reducing loads, especially through the use of infiltration devices and other natural solutions, and to continue maintaining good quantitative and chemical status of groundwater.

This document provides key recommendations and guidelines to survey water cycle, pollutant and stormwater mass balance to set targets and goals in urban drainage system that contribute jointly for relieving the sewer system as to strengthen the resilience of groundwater quality.

A. WATER AND CONTAMINANT MASS BALANCE AT THE FUNCTIONAL URBAN AREA LEVEL

STANDPOINT

Climate resilience is stronger if, despite increasing environmental pressures and more demanding weather conditions, burdens are not transferred to downstream or upstream areas.

Sustainable and responsible use of natural resources is the foundation and prerequisite of a circular economy.

The functionality of ecosystems and urban areas depends greatly on the sustainable and responsible use of water resources.

The sensitivity of a water resource to changes and pressures varies in each case. Generally, sustainability and responsibility can be maintained under moderate pressures:

- Abstraction of water from the aquifer in quantities up to one third of the dynamic reserves renewed annually.
- Prevention of substances that are toxic or accumulate in organisms from entering the groundwater.
- Limitation of the entry of all other substances that could potentially disperse into the environment.

The key parameters for monitoring changes in the water and mass balance, as well as the sustainability and responsibility of use, are listed in Table 1 and shown in Figure 1.

Table 1. Key parameters of changes in the water and mass balance.

Key parameters in the water and mass balance	Note
Annual effective precipitation ($P_{ef} = P - ETR$)	P=precipitation / ETR=evapotranspiration
Direct runoff to river (Q_{nep})	Runoff due to sealing
Groundwater recharge from precipitation (Q_{rec})	$Q_{rec} \approx P_{ef} - Q_{nep}$
Groundwater recharge from river (Q_{river})	Seepage through the riverbed
Flow through the aquifer ($Q_{vod} = Q_{rec} + Q_{river} + Q_{qw}$)	Total mass of water in motion
Pollutant concentrations at the entry point ($C_{background}$)	In the river or in groundwater inflow
Pollutant mass at the entry to groundwater (m_{in})	Compliance point POC1 at the groundwater table
Pollutant concentrations at the exit point (C_{out})	Outflow into the river or neighbouring aquifer
Change in groundwater level ($dGWL$)	Deviation from current state
Change in groundwater flow direction ($d\omega$)	Deviation from current state

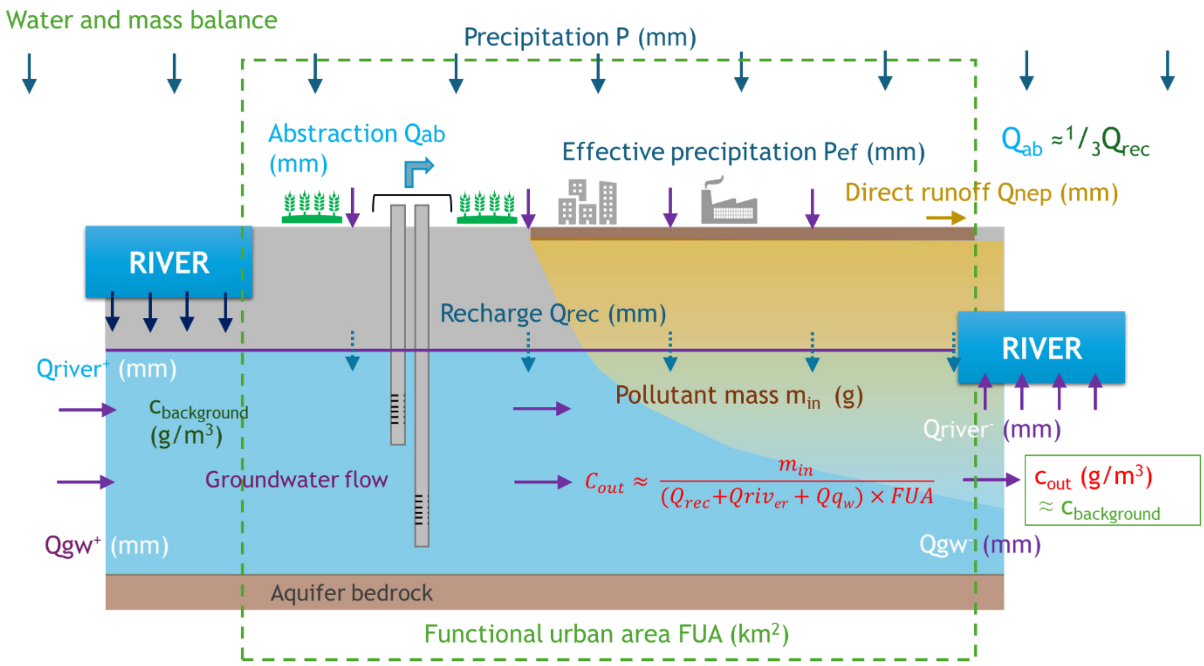


Figure 1. Schematic representation of key elements of the water and mass balance.

1. WATER CYCLE MASS BALANCE

1.1. Causes of long-term changes in water balance

Changes in water mass flows have, since the beginning of the 20th century (i.e., since the pre-industrial period), been more pronounced due to human interventions than due to climate change. The most important interventions include riverbed regulation for agricultural land, construction of water reservoirs for hydropower plants, and a significant increase in groundwater abstraction for population and industrial use. These interventions have greatly influenced changes in groundwater levels and flow directions.

For the future, the impacts of climate change must be increasingly taken into account. Changes in air temperature affect the main components of the water balance: surface runoff, precipitation infiltration, evapotranspiration, recharge from the river, and drainage into the river.

These changes affect groundwater level changes, groundwater flow directions, and water flow through the aquifer.

Climate change is first reflected in the atmospheric part in changes in annual values and seasonal distribution of minima and maxima. This is transferred into the lithospheric part of the water source and from the lithosphere back to the hydrological and atmospheric parts (Figure 2).

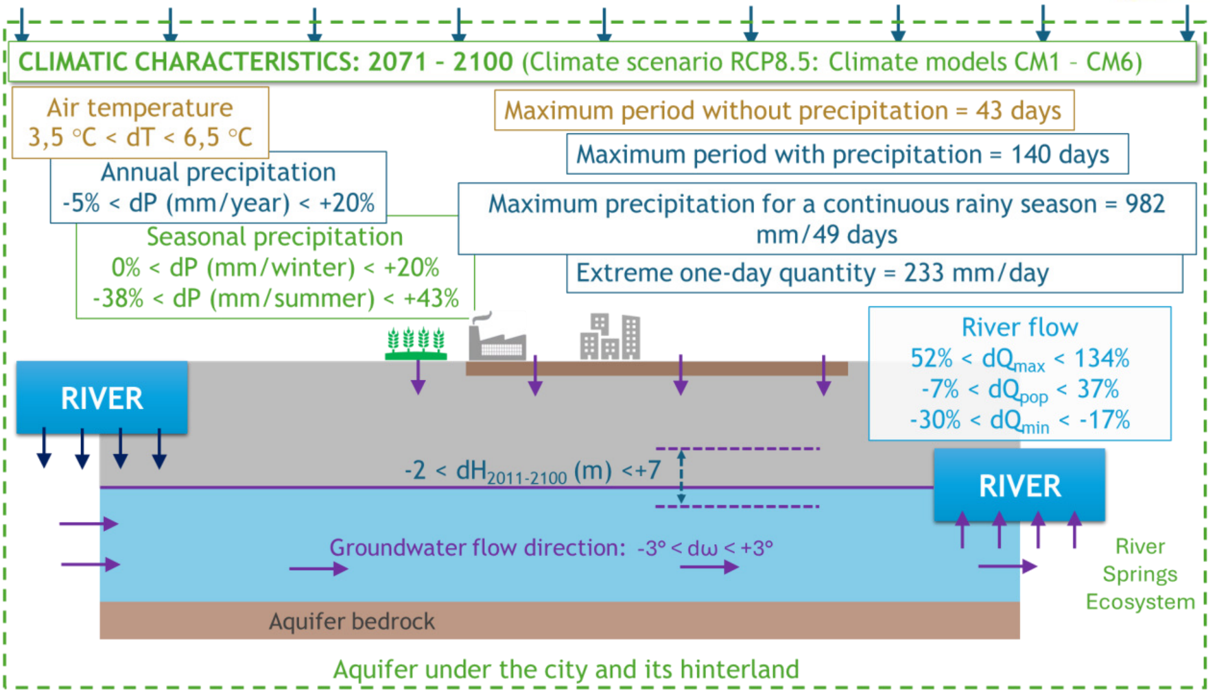


Figure 2. Illustration of the characteristics of climate change and their impact on the aquifer.

A detailed example of the analysis and monitoring of changes in the water balance is shown in Figure 3. The detailed diagram presents 15 different components of the water balance using the example of the Ljubljansko polje aquifer. The calculation example was made using a mathematical model based on the climate scenario RCP8.5 and the climate model CM4.

1.2. Importance of changes in water balance in the aquifer

- Change in groundwater level
  - The water reserve and retention capacity

A change in groundwater level (ΔH) in the aquifer means a change in groundwater reserves (dV_z). The aquifer is a water reservoir with a volume determined by the effective porosity of the aquifer (m_{ef}). Effective porosity is the proportion of interconnected pores from which water can drain by gravity and can therefore be exploited by pumping or stored there.

In an open sand-gravel aquifer, m_{ef} = 15% (1.5×10^{-1}), the volume of water retained in one metre of aquifer with an area A = 1 km^2 (= 100 ha = 1×10^6 m^2) is $dV_z = 1.5 \times 10^{-5}$ m^3.

A decrease in groundwater level means depleted groundwater reserves.

An increase in groundwater level means a reduction in retention capacity for stormwater.

- Yield of abstractions

A decrease in groundwater level reduces the yield of abstractions and increases the required pumping hight.

- Waterlogging

An increase in shallow groundwater level at the level of foundation soils leads to waterlogging of foundations or deeper underground parts of buildings. The rise of groundwater level can increase the influence area of infiltration devices and thus also waterlogging of neighbouring land or buildings.

- Other construction impacts

A decrease in groundwater level in compressible muddy (clayey and silty) layers causes water to drain from pores and consequently ground subsidence and damage to structures and installations.

An increase in groundwater level can increase buoyancy on structures, underground reservoirs, or pipelines and cause possible movements or damage.

An increase in groundwater level above sewer pipelines can increase drainage and thus the load on the sewer system.

An increase in water level in low stability or unstable soils can increase the risk of landslides or trigger, accelerate, or increase movements of foundation soils.

An increase in groundwater level in areas of open spaces in the underground (excavations, pipelines, tunnels, etc.) can cause washing of surrounding material into the voids, internal erosion, and damage to foundation soils and structures.

An increase in groundwater level in swelling layers causes deformations in foundation soils and damage to structures and installations.

- Natural retention capacities for pollutants

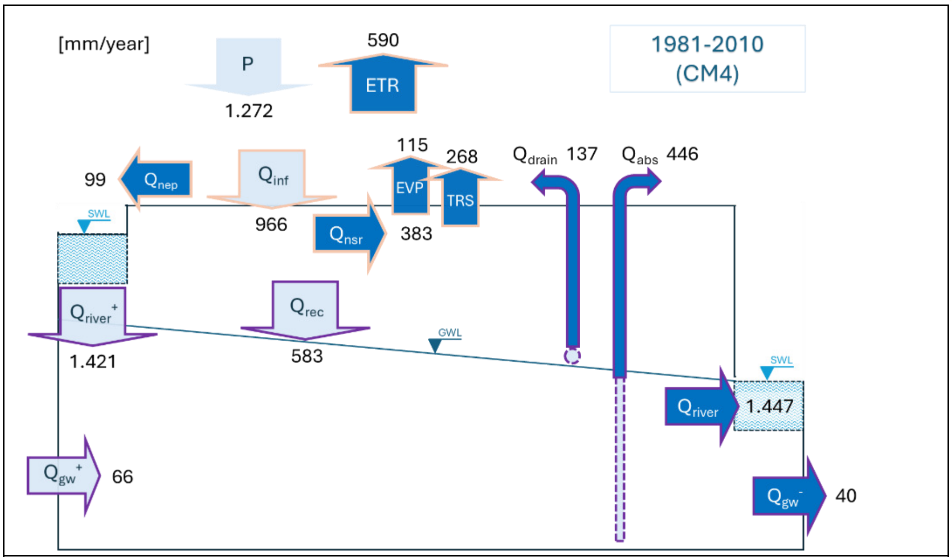
An increase in groundwater level reduces the thickness of the unsaturated zone and thus its ability to retain pollutants before they penetrate into groundwater and further spread with groundwater flow into the wider environment.

- Change in flow through the aquifer

A change in flow through the aquifer means a change in pollutant dilution, i.e., an increase or decrease in their concentrations. The change in flow results from a change in recharge from the river or precipitation. The change in water quality is consequently dependent on the quality of river water and the quality of soils and subsoils through which rainwater infiltrates.

- Change in groundwater flow direction

A change in the regime of groundwater recharge and abstraction also causes changes in groundwater flow direction. A deviation in flow direction also leads to a deviation in the path of pollutants and consequently to the transfer of pollution to other abstractions. A deviation in flow direction of 1° means a deviation of 17.5 m over a distance of 1 km.



1.715	*P* (mm)	Precipitation – average annual
133	Q_{nep}	Direct runoff
672	*ETR*	*Evapotranspiration*
140	*EVP*	Evaporation
303	*TRS*	Transpiration
443	Q_{nsr}	Near-surface runoff (*EVP* + *TRS*)
1.350	Q_{inf}	Infiltration
907	Q_{rec}	Recharge from precipitation ($Q_{inf} – Q_{nsr}$)
59	Q_{gw+}	Groundwater inflow
32	Q_{gw-}	Groundwater outflow
264	Q_{abs}	Abstraction
227	Q_{drain}	Drainage outflow
1.698	Q_{river-}	Outflow to river
1.255	Q_{river+}	Inflow from river (recharge)
1.043	P_{ef}	Effective precipitation (*P* – *ETR*)

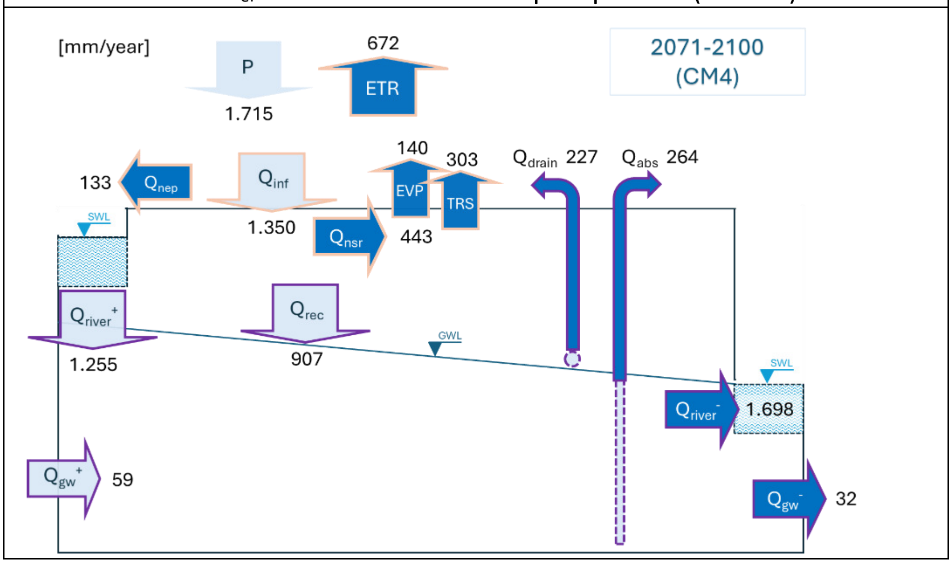


Figure 3. Schematic representation of water balance components under different modelled climate conditions.

1.3. Assessment of pollutant surpluses

1- Check the resilience of abstraction sites and water permits (yield, depth and pumping hight) for the drop of minimum water level for up to 2 m and define operational sustainability measures.
2- Check the resistance to waterlogging of underground constructions for potentially raised groundwater levels according to their spatial distribution (Figure 4) and define operational sustainability measures.
3- Check minimum distances of infiltration facilities (ref. 3.2.3).
4- Maintain or decrease the direct runoff.
5- Maintain the recharge from the river.

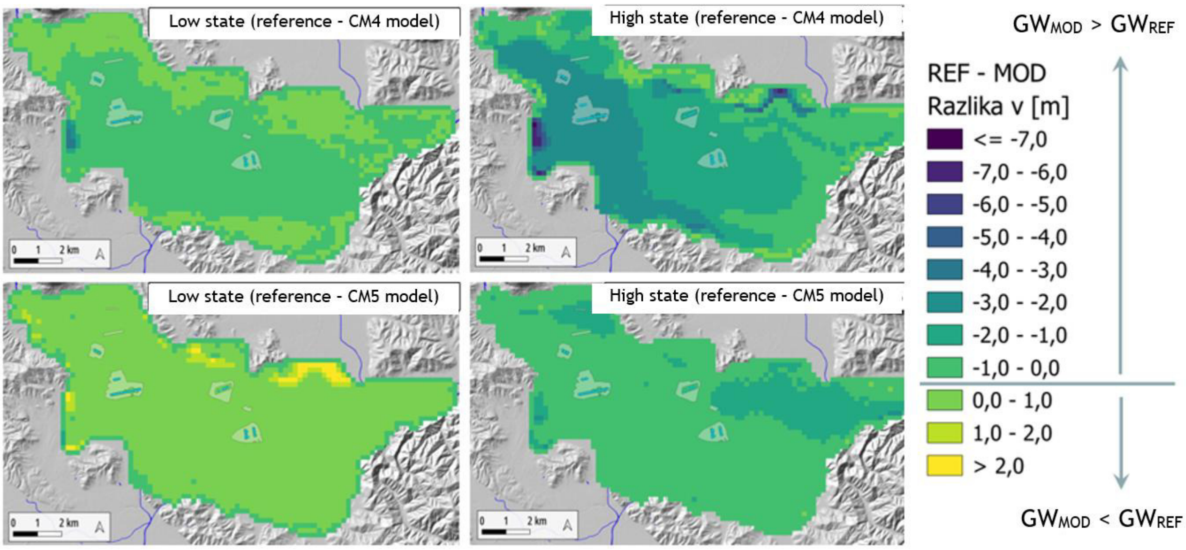


Figure 4. Potential changes in groundwater levels due to the impact of climate change (-raised / +decreased) – example of Ljubljana aquifer.

2. MASS BALANCE OF POLLUTANTS

2.1. Types of pollutants

The pollutant balance consists of various substances.

With increasing settlement, agriculture, and industry, the pressures on groundwater quality have greatly increased. High concentrations of nitrates and pesticides have appeared regionally, and more localised pollution due to emissions and losses of substances from industry, such as chromium (CrVI) and organic solvents (PCE, TCE).

At the beginning of the 21st century, with the introduction of common European water policy, the impacts of pressures were already significantly reduced. Today, we are primarily faced with ever new numerous pollutants that come with the increasing production of synthetic substances and products. These are mainly residues of pharmaceuticals, plasticisers, corrosion inhibitors, microplastics, and others.

For monitoring surpluses in groundwater, pollutants can be divided into two characteristic groups:

- Point pollution, which originates from smaller areas or points and is monitored at the cross-section of the pollution flow using the “transect method”.
- Diffuse pollution, which is present throughout the aquifer and is monitored by estimating the mass from average concentration values in the aquifer area.

2.2. Estimation of pollutant mass

2.2.1. Point sources – Transect method

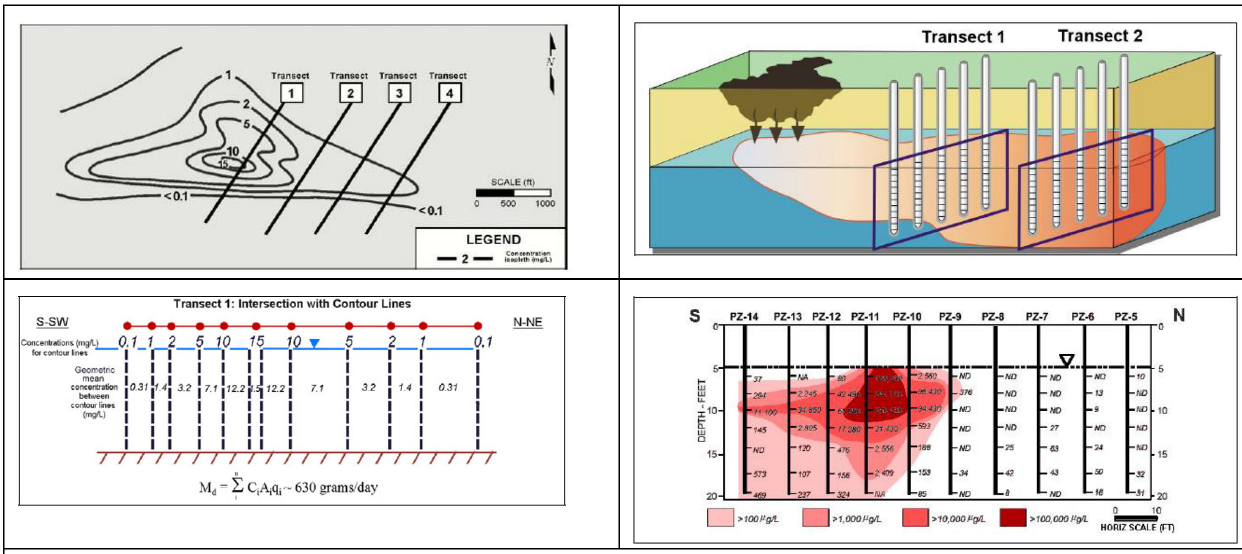
For pollutants that spread in a characteristic pollution plume, the transect method is most commonly used (Newell et al., 2003, Farhat et al., 2006). Depending on the availability of spatial data, it can be used in 2D or 3D analysis of the area. The method is based on setting a control plane perpendicular to the main direction of groundwater flow, which is divided into representative sections according to measured pollutant concentrations. For each section, the partial mass flow is calculated, taking into account the Darcy velocity and the area of each section. The sum of all partial flows represents the total mass discharge (M_d) through the selected transect (Figure 5):

$$M_d = \sum_{i=1}^{n} q_i\, C_i A_i \qquad (1)$$

Where:
M_d: total mass discharge of pollutant through the transect [g/day]
q_i: Darcy velocity or specific water flow, perpendicular to the transect, in section i [m/day]
C_i: pollutant concentration in section i [mg/L]
A_i: area of section i of the transect [m^2]
n: total number of sections into which the transect is divided.

Advantages: enables direct quantification of flow in a real system.

Limitations: requires good spatial distribution of measurements and precise knowledge of hydraulic parameters.



Newell, C.J., Conner, J.A. and Rowen, D.L. (2003), Groundwater Remediation Strategies Tool, Houston, Texas.

Farhat, S. K.; Newell, C. J.; Nichols, Eric M. (2006). Mass Flux Toolkit. To Evaluate Groundwater Impacts, Attenuation, and Remediation Alternatives. User's Manual. Version 1.0., March, 2006. GSI ENVIRONMENTAL INC HOUSTON TX. https://apps.dtic.mil/sti/citations/ADA637523

Figure 5. Examples of the use of the transect method in 2D and 3D areas (Source: Newell et al., 2003, Farhat et al., 2006).

Figure 6 and Figure 7show two examples of contamination plumes of two different pollutants, each with a transect and defined representative measurement points for tracking the mass of the pollutant.

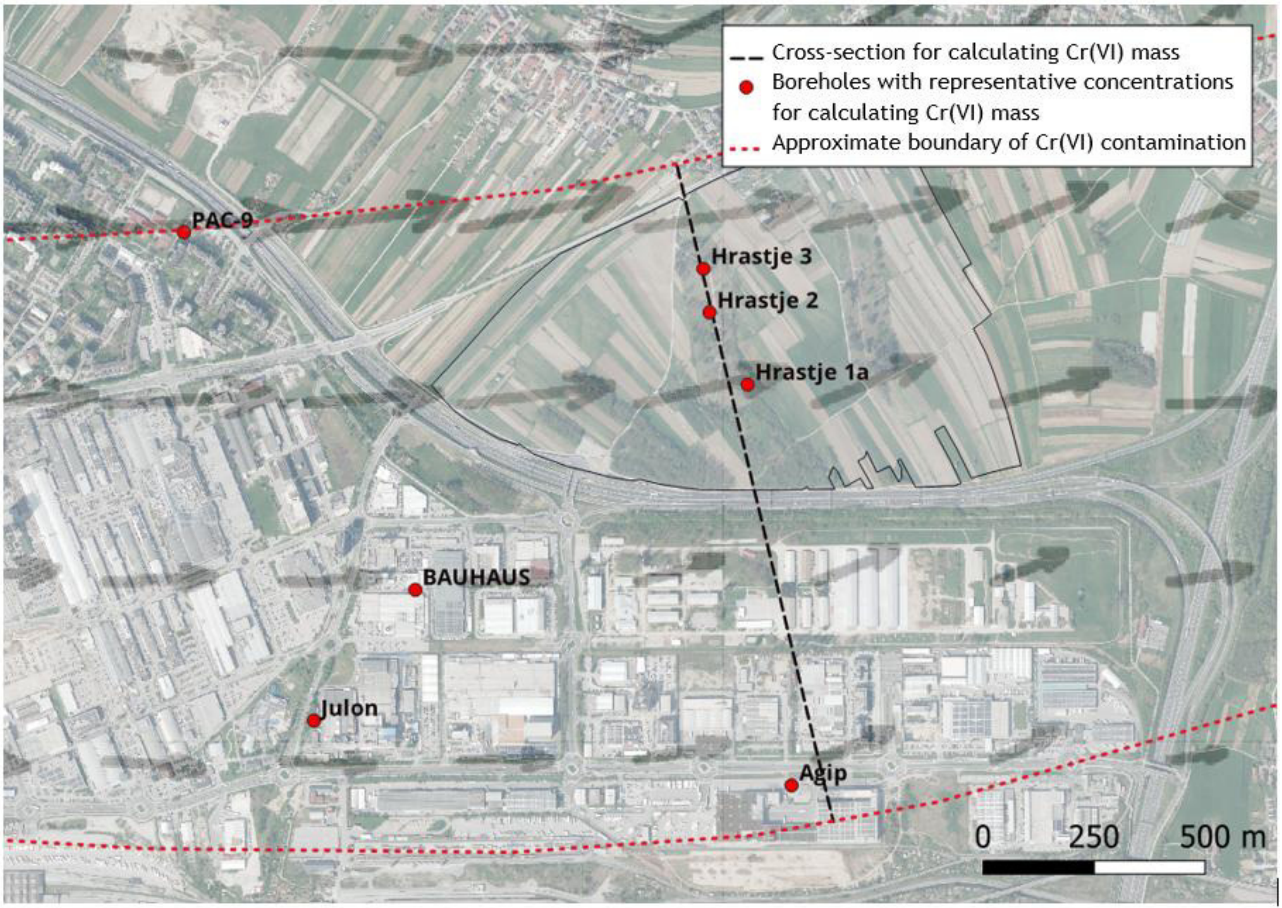


Figure 6. Example of a contamination plume with hexavalent chromium and the selected transect with defined measurement points.

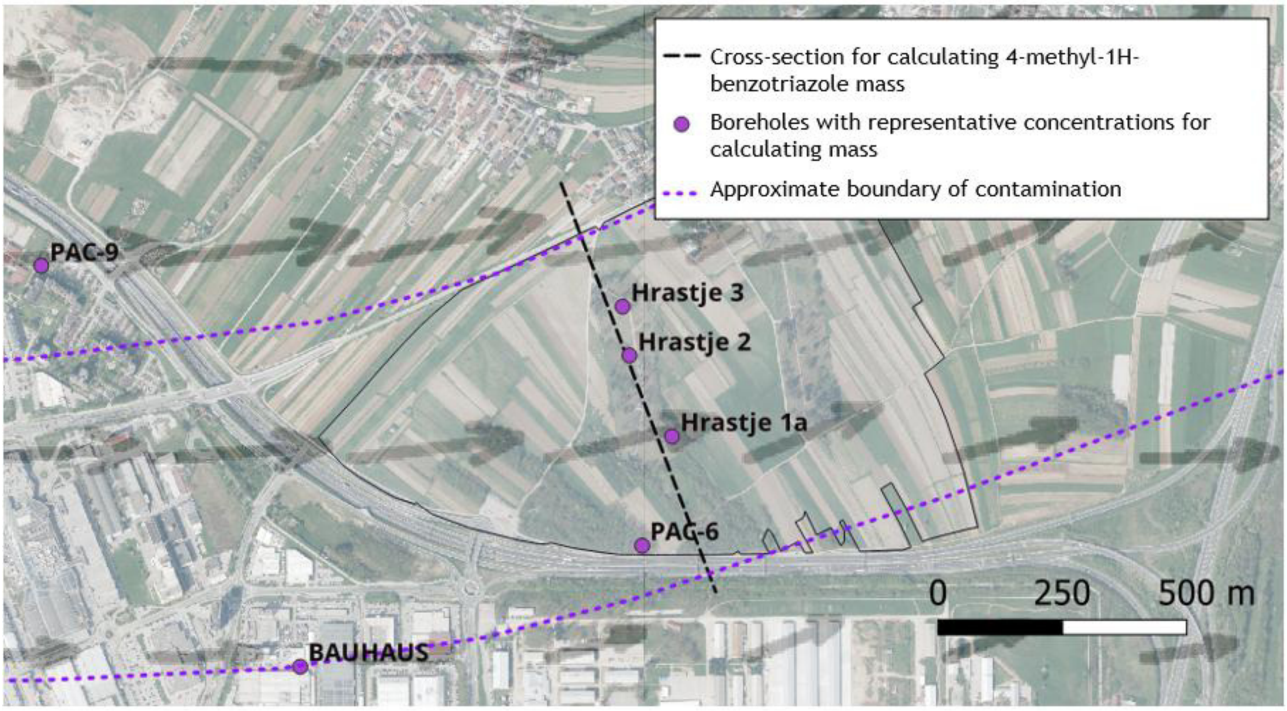


Figure 7. Example of a contamination plume with benzotriazole and the selected transect with defined measurement points.

2.2.2. Diffuse sources – average concentration method in the aquifer area

- The average concentration method

Estimating the mass of a pollutant based on average concentration values throughout the aquifer is mainly appropriate in cases of diffuse pollution, which occurs at the level of the entire aquifer. Such cases are typical for pollutants with a pronounced natural background and individual local anomalies, where measurements are available from a large number of monitoring points and longer time series of data.

Advantages: enables a quick, approximate estimate of the total mass or flow of the pollutant through the aquifer.

Limitations: the result is only a rough, non-explicit estimate that does not take into account spatial heterogeneities and local variations in concentrations or flow.

- Solute transport model method

The mass flow can also be estimated using analytical or numerical transport models that link concentration data with modelled groundwater flow velocity.

Advantages: enables simulation of different scenarios, including biodegradation and dispersion.

Limitations: the result depends on the quality of input data and model assumptions.

The calculation of the average value and trend of concentration is carried out in two ways, using two types of measurement points (Figure 8, Figure 9):

A) with measurement points that are part of regular monitoring, with at least twice-yearly seasonal analysis and are well distributed spatially, so that they can represent the characteristics of the distribution and transport of pollutants in the water source;

B) with measurement points that have the longest continuous time series of observations and can continue to be maintained for the purpose of tracking long-term trends.

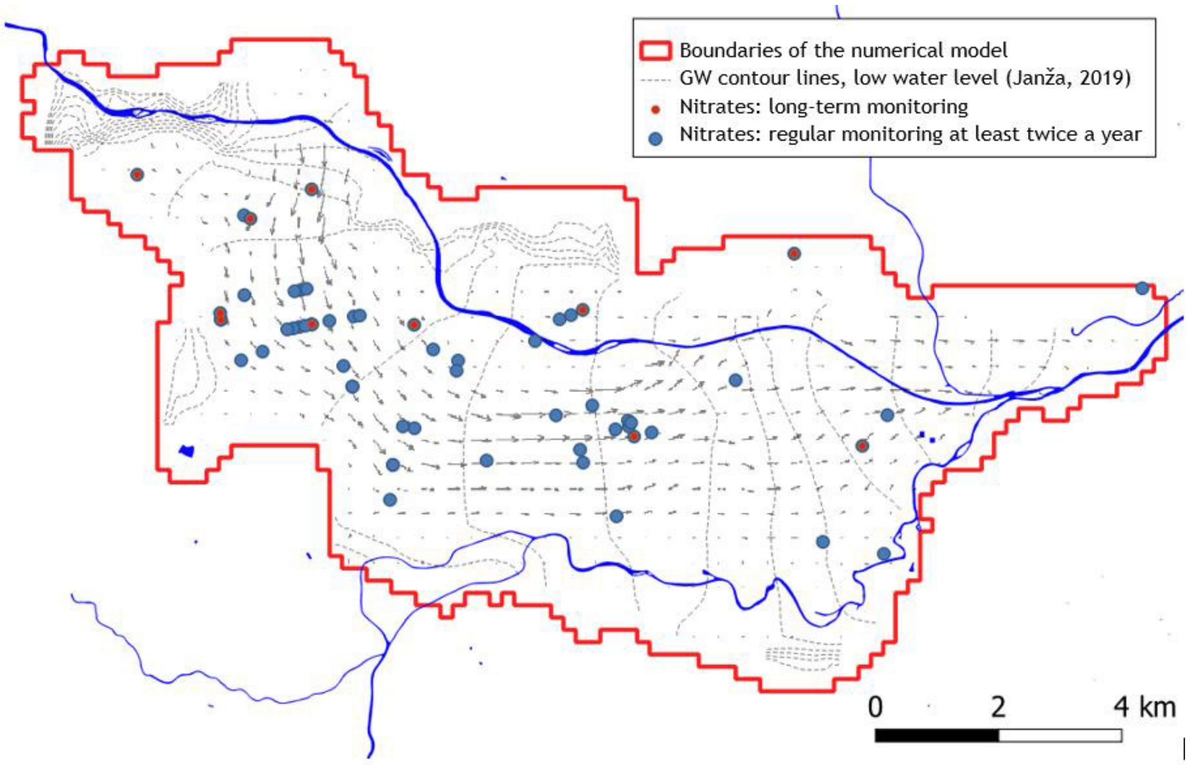


Figure 8. Distribution of type A (red) and B (blue) measurement points in the example of the Ljubljansko polje aquifer.

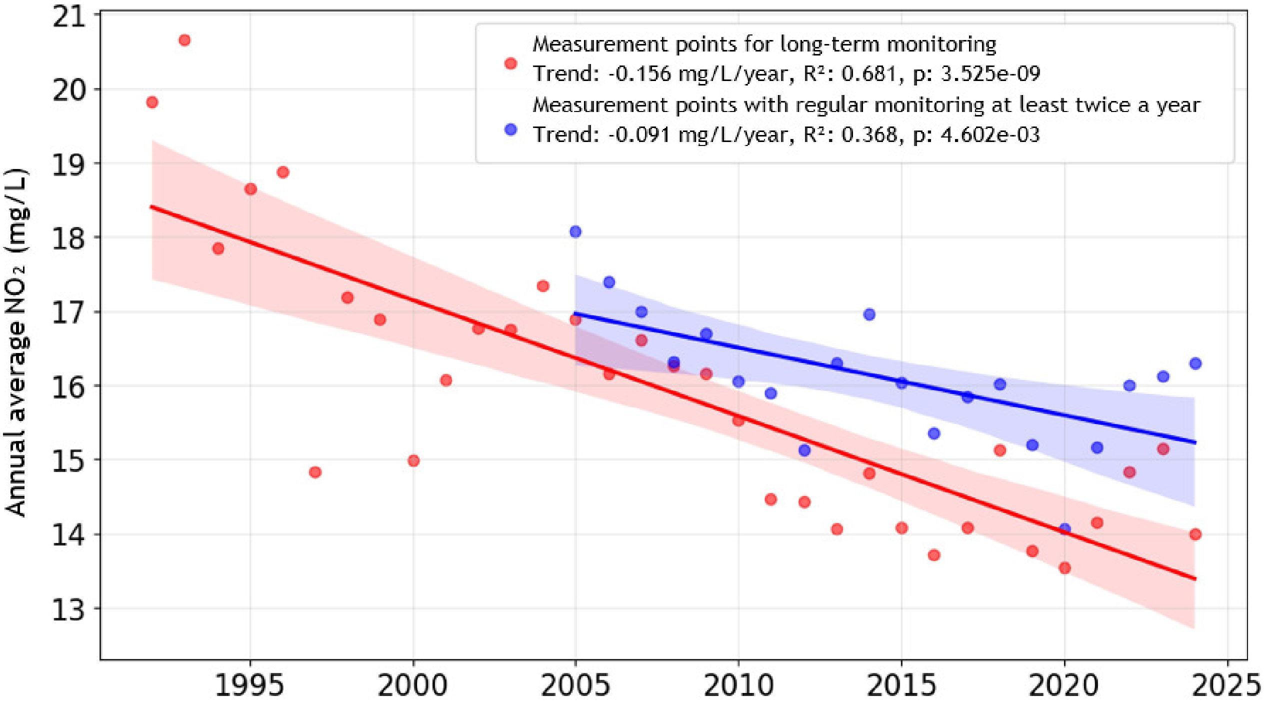


Figure 9. Long-term and short-term trends of average nitrate values in the example of the Ljubljansko polje aquifer.

A comparison of the average values and trends calculated using the "long-term" and "regular" sets of measurement points shows a significant difference (Figure 9). The difference in trends is the result of much higher loads before the year 2000. However, both trends indicate the end of a significant decrease in concentrations after 2015.

The difference in the average value between the two sets of measurement points is due to the fact that the long-term measurement points are mainly located in abstraction areas and less in more heavily loaded areas.

The example of the analysis carried out shows that it makes sense to continue monitoring the trend with the regular set of measurement points. For trend analysis, the "long-term" set of measurement points is no longer as important. It is important that the "regular" set consists of measurement points from abstraction areas as well as from more heavily loaded areas. In this way, it is possible to monitor the total mass together or to target each mass separately.

2.3. Setting targets and goals

A surplus of pollutants at the level of the functional urban area occurs if the total mass of pollutant that enters the groundwater is not sufficiently diluted to avoid burdening the downstream area or water source.

The most sustainable situation is when the amount of water from effective precipitation (P_{ef}) is sufficient for dilution, or even better, when the amount of groundwater recharge from precipitation (Q_{nap}) is sufficient.

With a simple mixing ratio, it is possible to calculate the required reduction in the mass of pollutant that is lost to the subsoil and groundwater (Figure 10).

$$C_{out} \approx \frac{m_{in}}{(Q_{in} + Q_{river} + Q_{GW}) \times FMO}$$

Where:

C_{out}: concentration of pollutant diluted in effective precipitation [g/m^3]

m_{in}: mass of contaminant entering groundwater table [g]

Q_{river}: recharge form the river [m]

Q_{gw}: recharge from groundwater inflow [m]

FMO: functional urban area [m^2]

The example in Figure 10 *shows that dilution from effective precipitation (P_{ef}) is not sufficient, nor is it sufficient if we also add recharge from the river (Q_{river}+).*

CrVI and nitrate are considered pollutants that are present in the natural environment. Atrazine (AT) and benzotriazole (BT) are considered synthetic organic pollutants, hazardous to water.

Atrazine is a recognised hazardous substance, while benzotriazole is treated as hazardous until the consequences of its spread in the environment are known. Atrazine is a distinctly old burden, long since completely banned, and we have little influence on its release from old pollution; in fact, we are only discovering its sources.

Hexavalent chromium probably has its most important source in old pollution retained in the unsaturated zone of the aquifer from the time of the city's greatest industrialisation; however, there are still possible active sources (operating facilities), of which only some are known and recorded.

Nitrogen loads from agriculture and sewerage were significantly reduced by 2015, but progress in reducing losses has stalled over the past 10 years.

An assessment of the mass of benzotriazoles in groundwater shows that around 1,000 kg (one tonne) of substances containing this compound enter the groundwater each year. The main reason for these losses is very likely the public's unawareness that such substances (for example, heat transfer fluids in cooling or heating systems) must not be released into the environment.

*Example of defining management objectives based on mass balance analysis (*Figure 10*):*

The reduction of nitrogen losses to groundwater should continue through regular sewer maintenance and improved agricultural practices. Total losses should be reduced by a further 26% over the next 20 years, gradually but consistently and regularly. In agriculture, this should be achieved mainly by increasingly effective and practical implementation of integrated farming practices. This will prevent groundwater quality from deteriorating again, despite climate change and more intensive development of settlements and activities.

The management of substances containing benzotriazoles should be better organised, appropriate disposal enabled, and the public informed – with the aim of reducing environmental losses by 71%.

Sources of hexavalent chromium should be identified and their release into the subsoil prevented. During construction in critical areas, any potentially contaminated material should be identified and either isolated or removed in accordance with existing guidelines. Current pollution plumes should be systematically traced to their sources. For existing facilities (active sources), regular checks of the adequacy of sewer connections should be ensured. Current losses should be reduced by 67%.

The trend of residual atrazine concentrations should continue to be monitored at sites where elevated concentrations have been found. When buried waste or contaminated material is discovered, care should be taken to ensure it is not pesticide residues or their packaging. In such cases, the material should be properly isolated, removed, or simply monitored.

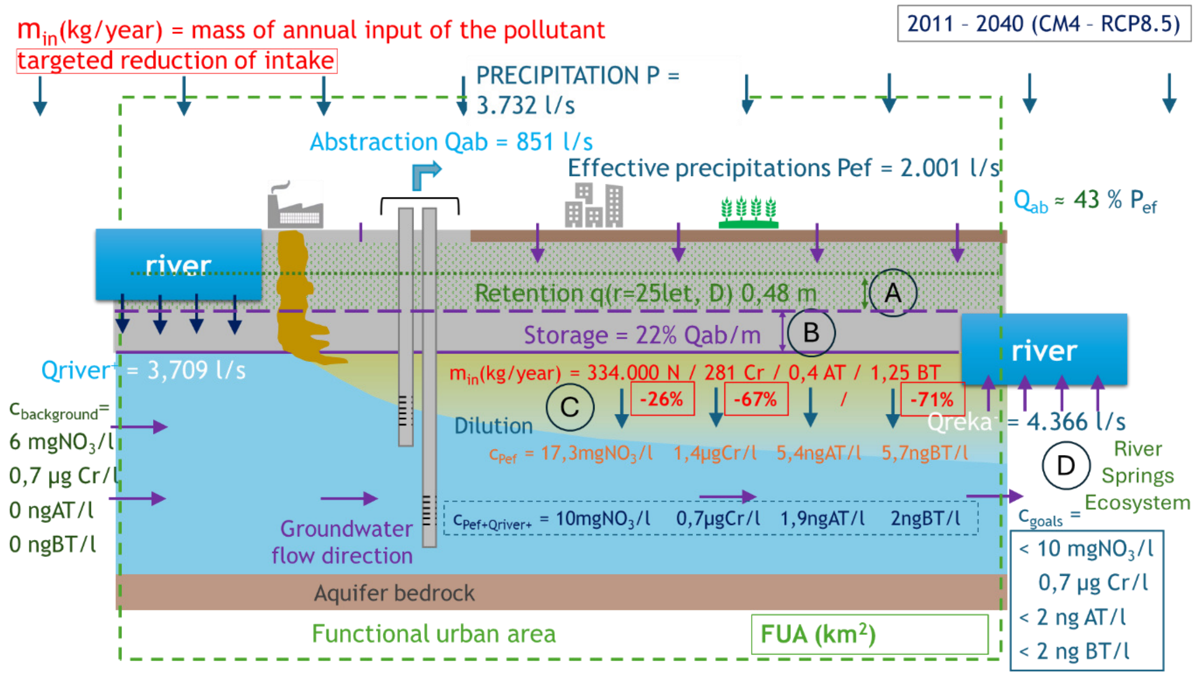


Figure 10. Illustration of the assessment of pollutant surplus in the water and mass balance for the Ljubljansko polje aquifer.

3. STORMWATER BALANCE

3.1. Roof water

- Roof area

At the level of the spatial plan of the local community and the functional urban area, the most important water mass surpluses come from roofs, as this is relatively clean rainwater that should be infiltrated or retained locally as much as possible. The first step is to analyse roof areas. Data on the size and distribution of roofs are obtained from spatial records, for example, the building cadastre.

> *In the City Municipality of Ljubljana, the total roof area is approximately 1,619 ha, which represents about 6% of the municipality's total area. For the city of Varaždin, available data show that the total roof area is about 271 ha, which is around 4–5% of the total area considered. Note: As the entire municipality is not connected to the sewer network, these roofs account for a disproportionately large share of the total surfaces contributing runoff to the sewer system.*

The surplus water mass from roof surfaces can also be estimated at the level of the municipal spatial plan. At the level of the municipal spatial plan (OPN), it is possible to calculate the volume of water represented by a rainfall event of a certain return period and how much retention or infiltration would be needed to reduce peak runoff.

The analysis of roof areas can also be carried out according to the land use of the municipality.

> *For Ljubljana, in the calculated water balance, residential areas (S) contribute the most to stormwater runoff—almost half of the total runoff (49%), followed by central activities (C) with 22% and industrial activities (I) with 10%. It is also worth mentioning the indicator "roof_area/OPN_area", which shows the share of roofs relative to the total area of each land use. The highest values are found in central activity areas (62%), residential areas (53%), and special areas (53%), which further confirms the high degree of development in these areas.*

- Annual quantity of roof water

In the next step, a simplified hydrotechnical calculation of the maximum possible runoff from roofs during heavy rainfall is carried out. The rational formula can be used:

$$Q = C \times i \times A \qquad (3)$$

where

Q is the runoff (m^3/s),

C is the runoff coefficient,

i is the rainfall intensity, and

A is the relevant area.

For roofs, a runoff coefficient of $C = 0.9$ is assumed, meaning that about 90% of the precipitation falling on the roof runs off, while 10% is retained on the surface, evaporates, etc.

> *The roof area of approximately 1,619 ha in the City Municipality of Ljubljana and 271 ha in the City of Varaždin can contribute about 15.2 and 2.3 million m^3 of stormwater runoff per year, respectively. Roofs are therefore an important factor in stormwater runoff.*

- Roof water runoff during storms

The intensity of the rainfall is determined according to design assumptions—for example, a 15-minute rainfall event with a frequency of twice a year has, according to technical guidelines, an intensity of about 131.8 l/s/ha. This corresponds to approximately 0.132 litres per second per square metre or about 8 mm of rain in 15 minutes. With these data, the so-called reduced roof area and peak runoff can be calculated.

> *In Ljubljana, the total reduced roof area (considering $C = 0.9$) is about 1,457 ha, and with a rainfall intensity of 131.8 l/s/ha, the theoretical total runoff would reach 192 m^3/s if a uniform heavy rainfall covered all roofs simultaneously. In Varaždin, the total reduced roof area is about 244 ha (271 ha × 0.9). With the same 15-minute rainfall intensity (131.8 l/s/ha), the maximum runoff from all roofs would be about 32 m^3/s (peak flow) if the rainfall covered the entire city at once. This is much less than in Ljubljana (where, due to the larger roof area, the calculation is 192 m^3/s), but it still indicates a very large instantaneous stormwater flow, which would, if not managed, heavily burden the sewer system.*

Naturally, this scenario is a simplification. In reality, rainfall events rarely affect the entire area uniformly; given the large extent of roof surfaces, a 5-minute design storm is not suitable for assessing overall peak surface runoff; and other factors also apply. However, it is intended as an indicative tool for assessing potential runoff and the corresponding need for mitigation measures.

- Retention volumes and areas

> *In Ljubljana, for a 25-year, 15-minute rainfall event (322 l/s/ha) in the MOL area, about 700,000 m^3 of water would need to be retained to prevent overloading the sewer system. For Varaždin, which has a smaller roof area, this amount is proportionally smaller—we estimate it to be on the order of 0.1×10^6 m^3 (about 100,000–120,000 m^3).*
>
> *If this amount were to be retained on the surface, representing 10% of the reduced roof area in Ljubljana, retaining 700,000 m^3 would require about 146 ha of area to a depth of 0.48 m of water (*Table 2*).*

Table 2. Comparison of runoff from 5-, 25-, and 50-year 15-minute rainfall events from roof surfaces with pre-development runoff and the required retention volume (V_z) or height (ΔH) for the OPN MOL area and an individual roof of 200 m².

$q_{(r,D)}$ [*r*(let), *D*(minut)]	OPN MOL			Streha	
Initial state - grass	Runoff (l/s)	V_z (m³)	*ΔH* (m)	Runoff (l/s)	V_z (m³)
$q_{(5,15)}$=233 l/s/ha	37,723	0	0	0.47	0
New state - roofs					
$q_{(5,15)}$=233 l/s/ha	339,504	408,279	0.28	4.2	5.0
$q_{(25,15)}$=322 l/s/ha	469,186	699,991	0.48	5.8	8.6
$q_{(50,15)}$=367 l/s/ha	534,756	860,272	0.59	6.6	10.6

Varaždin has a much smaller total runoff; if we assume that 10% of the sealed surfaces in the city can be used for temporary stormwater retention (meadows, car parks, floodplains, etc., which would be about 70–80 ha in the case of Varaždin), the water depth for retaining a 25-year rainfall event would be only about 0.15 m (15 cm). This shows that volumetric retention of an extreme rainfall event in Varaždin is feasible with relatively shallow retention basins or floodable surfaces.

For the practical implementation of roof water infiltration, it is necessary to ensure sufficiently high soil permeability or infiltration area A_p. From the Ljubljana example, it follows that a permeability coefficient $k \geq 2.61 \times 10^{-5}$ m/s (≈0.00225 m/day) would be sufficient for infiltration devices to absorb the runoff from a 25-year rainfall event within a few hours (so that the retention volume does not overflow). If $k \geq 3.22 \times 10^{-4}$ m/s, the entire volume of an extreme rainfall event could be infiltrated directly without surface water accumulation.

In the context of Varaždin, measured soil permeabilities are mostly much higher than these thresholds (e.g., >4.8 m/day = 5.56×10^{-4} m/s in automorphic gravelly soils), so it is theoretically possible to infiltrate the entire roof runoff where appropriate infiltration systems are installed. Of course, local conditions must be taken into account—in some western edge areas with $k \sim 1 \times 10^{-7}$ to 5×10^{-6} m/s, infiltration would not be effective, and alternative solutions (retention, drainage) would be needed.

In the next phase, we check how many of these areas have a certain permeability, how many roofs can be fully infiltrated, and what can be managed with retention.

3.2. Setting targets and specific actions

3.2.1. Infiltration and retention potential

To illustrate the surplus at the level of a single building, let us take as an example a building with a roof area of 200 m². With a runoff coefficient of $C = 0.9$, the reduced roof area is 180 m². For such a building, the surplus of rainwater is 5 m³. We assume that the building is in a sewered area with a protection level for city centres and industrial zones, i.e., for rainfall events with a return period of 5 years and a flooding frequency of once every 30 years. The sewer system allows a throttled discharge for emptying the retention tank at 10 percent of the site runoff during a 15-minute rainfall event with a 5-year return period, which is 23.3 l/s/ha.

For an open retention tank, which would be on an area of one tenth of the sealed surface, a water depth of 0.28 m would be required for such a volume. For a buried retention tank with 30% porosity, a depth of 0.93 m would suffice.

If the infiltration capacity were 4.7×10^{-4} m/s, an infiltration area of 1 m^2 would be sufficient to return the entire 5-year rainfall event to the water cycle instead of discharging it into the sewer. With an infiltration capacity of 2.61×10^{-5} m/s, the entire area under the retention tank, i.e., 18 m^2, would need to be used for infiltration. If there were 9 m^2 of land with an infiltration capacity of 4.7×10^{-4} m/s, a retention tank would not be necessary. The calculation is made using the rainfall method (see Figure 11).

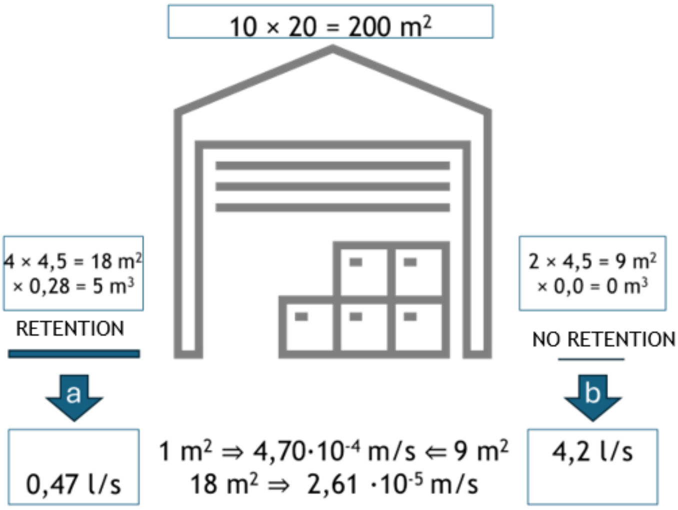
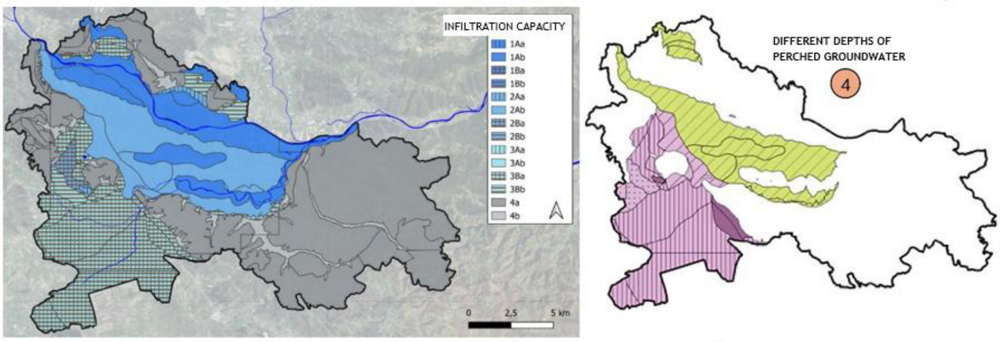


Figure 11. Surplus water mass due to roof water runoff (5-year rainfall event).

To assess how many roofs can be fully infiltrated and which require retention or throttled discharge, the layer of roof surfaces can be overlaid with a map of infiltration capacities. Such maps usually distinguish areas with good, medium, and poor infiltration capacity.

3.2.2. Priorities for infiltration

In Ljubljana, about 16% of building areas are on foundation soils with good infiltration capacity, 46% on medium, and 29% on low infiltration capacity. The remaining roof areas (9%) are in areas where the bedrock is at or near the surface. Low infiltration capacity and simultaneously limiting groundwater depth (< 3 m) are characteristic mainly for the southern part of Ljubljana (see Figure 12).



	Hydraulic conductivity	Infiltration capacity	Infiltration capacity
1: good	$k > 1\times10^{-4}$ m/s	$q_p > 6$ mm/min	$q_p > 1000$ l/s/ha
2: medium	$1\times10^{-5} < k$ (m/s) $< 1\times10^{-4}$	$0.6 < q_p$ (mm/min) < 6	$100 < q_p$ (l/s/ha) < 1000
3: poor	$<1\times10^{-5}$ m/s	<0.6 mm/min	<100 l/s/ha
Groundwater directly above the bedrock			
Groundwater in valley			

1

Overlaying strata	Depth to the groundwater
A: <3 m	a: <3 m
B: >3 m	b: >3 m
2	3

Figure 12. Infiltration capacities of the upper layers in the area of the City of Ljubljana. Source: Prestor et al., 2025

16% of roofs could be priority for infiltration of the entire storm water. 46% of roofs could be priority for partial infiltration and overflow. 38% of roofs could be a priority for allowed discharge and overflow.

Most buildings therefore require information on the permitted discharge quantity. For planning interventions, it is essential that initial information on the allowable discharge into a watercourse or the public sewer system, as well as the possibility of establishing an overflow to floodable areas, is already considered at the proposal and conceptual design stages.

For the assessment of the possibility of infiltrating rainwater from roofs in the city of Varaždin, four areas with different infiltration capacities were defined: areas with very good infiltration capacity (permeability > 4.8 m/day), areas with moderate infiltration capacity (1.4–4.8 m/day), areas with low infiltration capacity (0.01–0.5 m/day), and areas with very low permeability (e.g., epigley soils, wetland areas). In the pilot area of Varaždin, automorphic soils with high permeability predominate—about 60% of roofs are located in areas with sufficient infiltration capacity, where it is possible to fully infiltrate rainwater without the need for retention; about 25–30% of roofs are in areas with moderate infiltration capacity, where partial infiltration is possible, and the remainder must be retained or drained; the remaining 10–15% of roofs are in areas with low or very low infiltration capacity, where infiltration is limited or not feasible—in these cases, retention measures and throttled discharges into the sewer must be planned.

As in Ljubljana, it is also important in Varaždin for most buildings to obtain information on the permitted discharge into the sewer already at the conceptual design stage. This enables the planning of appropriate retention or infiltration systems that ensure sustainable water management and reduce the risk of flooding and sewer overload.

3.3. Redirecting roof runoff to infiltration

Guidance for disconnecting roof water from the sewer system and transitioning to an infiltration system can be provided by the public stormwater drainage and treatment service operator to individual users during inspections of internal connections, especially during renovations or new constructions.

In many European countries, utility service providers and local authorities actively encourage property owners to disconnect roof downpipes (gutters) from the public sewer and infiltrate rainwater on their own plot. Such incentives are motivated by environmental goals (relieving the sewer system, reducing flooding, improving groundwater) and are supported by legal frameworks and financial mechanisms. In practice, this is implemented in various ways: through legal obligations, technical guidelines and brochures for residents, financial incentives, and advisory programmes. Below are examples of good practice, including links to regulations, municipal measures, and possible subsidies or advisory projects.

Legal requirements and objectives: Some countries (e.g. Switzerland, Belgium) mandate the infiltration of clean rainwater on the plot, in line with environmental objectives and regulations. In France, national action plans (2022–2024) encourage local measures for sustainable rainwater management.

Technical guidelines and brochures: Operators often issue manuals and instructions for residents. In Switzerland, cities offer informative brochures on drainage and infiltration for homeowners, while in France, associations (e.g. ADOPTA) and utility companies prepare guides ("Je débranche ma gouttière") for disconnecting gutters and sustainable rainwater use.

Financial incentives and advice: The "polluter pays" principle applies: where roof water is connected to the sewer, a special fee is charged (e.g. in Germany, per m^2 of impermeable surface, in Slovenia per m^2 of roof area). Many municipalities or local communities offer subsidies for disconnection or retention of rainwater. In Flanders (Belgium), when sewer separation is mandatory, an expert ("afkoppelingsdeskundige") advises owners, prepares a disconnection plan, and helps secure financial support.

Good practices in Europe show that a combination of clear regulations, financial incentives, and practical guidance successfully encourages individuals to disconnect roof water from the sewer. In environments where the operator provides the customer with a solution in writing during connection inspections, the likelihood of the owner taking action increases, as they have a strong motivation (e.g. lower costs, regulatory compliance) for concrete action (a plan or instructions on how to arrange infiltration). Thus, when deciding whether to invest in the renovation of an inadequate, outdated sewer connection or in an infiltration system, the owner is more likely to choose to invest in the infiltration system.

Such measures also support local and national environmental objectives (fewer floods, cleaner watercourses, groundwater recharge) and represent an effective model, which in many places is further enhanced by advisory services and financial assistance, so that as many properties as possible are “disconnected” from the sewer and reconnected to the natural water cycle.

3.4. Minimum distances from buildings and plot boundaries

When designing infiltration systems, in addition to hydraulic capacities (see Sections 3.1 and 3.2), special attention must also be paid to appropriate minimum distances of infiltration devices from buildings, infrastructure, and neighbouring plots. Properly chosen minimum distances ensure that the infiltration of rainwater does not endanger the stability and safety of structures (e.g., foundations, basements, roads, or water supply lines) and does not cause damage or disturbances to neighbouring land.

Minimum distances of infiltration devices from own buildings: The infiltration device must be positioned so that it does not compromise the stability of the structure or cause water ingress into basements or foundations. The soil around the building becomes moistened due to infiltrated water, and the groundwater level may rise—both can affect the foundations, especially in less permeable soils. Various standards (DWA, SIA) therefore require minimum setbacks from the building, depending on the depth and type of foundation and hydrological conditions:

- The recommended minimum setback of the infiltration device from the building is approximately 1.5 times the depth of the infiltration device excavation. For example, if the infiltration shaft is 2 m deep, it should be at least about 3 m from the foundations of the nearest building. This distance ensures that the saturated zone around the infiltration device does not reach the foundations directly.
- For buildings with a deep basement or more demanding waterproofing, minimum distances must be determined with particular care. If the building has no basement (shallow foundations), the minimum distance is determined according to the depth of the foundations in the ground. If the exact depth of the foundations is not known for older buildings, a conservative criterion is used: a 1:1 (45°) spread of water from the bottom of the foundations upwards is assumed. This means the infiltration device must be placed outside this angle—for example, if the foundation is 1 m below the surface, the infiltration device should be at least 1 m from the edge of the foundation plus an additional 0.5 m safety margin. This minimum distance ≥ 0.5 m from the projection of the foundation edge ensures that infiltrating water does not seep directly into the backfill material next to the building wall.
- If the building’s foundations are well waterproofed, infiltration nearby does not pose a direct threat of water ingress into the basement, but construction impacts must still be considered (e.g., a rise in groundwater can cause additional buoyancy forces on the structure, especially for lighter constructions). Even in this case, minimum distances of at least 1.5 times the depth of the infiltration device are recommended, unless the designer can demonstrate with geotechnical calculations that it is safe at smaller distances.
- For larger centralised infiltration fields or tanks that infiltrate water from a larger area at one point, the distance from the edge of the infiltration device to the nearest building should be greater than the average diameter (width) of the infiltration device. For example, if there is an underground retention or infiltration block 4 m wide, it should not be placed right next to the building’s

foundations—the minimum distance should exceed 4 m, so that there is enough unsaturated ground between the system and the building to absorb and disperse the water.

Minimum distances from other structures and infrastructure: Appropriate distances must also be ensured to other construction elements on or near the plot. These include roads, driveways, retaining walls, and utilities (water supply, sewerage, electricity), which could be threatened by rainwater.

- Infiltration systems should not be built directly next to road edges or roadside ditches. Large amounts of discharged water can loosen the road’s bearing layer or cause erosion in the verge. It is advisable to place the infiltration device at least a few metres from the road edge. In practice, infiltration should be arranged so that water drains away from the road structure, either by terrain slope or by directing infiltration to the other side. If this is not possible, construction measures (e.g., drainage with edge outflow) must be implemented to keep the road protected.
- Underground utilities, especially water pipes, require careful handling. The immediate proximity of the infiltration device can affect them: in the event of a water pipe leak, water would more easily flow into the infiltration device, and conversely, infiltration can cause constant wetting around the pipe, changing its bedding or possibly causing contamination (if hazardous substances enter the infiltration device). Guidelines therefore advise that infiltration devices should not be placed directly above or next to public water pipes, but rather on the other side of the plot or at least outside the excavation area of the utilities. This way, there is always a layer of dry or less wet soil between the infiltration device and the pipe, maintaining stability. If infiltration is carried out near sewer pipes, it must be ensured that stormwater does not inadvertently enter the sewer (e.g., through poorly sealed joints), thus negating the purpose of disconnecting rainwater from the sewer system.
- The same applies to other structures, such as retaining and supporting walls or fence foundations: the key point of the minimum distance is that soil saturation does not reach the area bearing the load of these structures. For example, with retaining walls on a slope, an infiltration device placed too close can saturate the soil behind the wall and thus reduce slope stability (increased pore pressure can lead to slippage). The safety minimum distance is determined according to the height of the wall and the geomechanical properties of the soil—the higher the wall and the steeper the terrain, the greater the distance required. In some places, guidelines limit infiltration at the top of the slope and recommend draining excess water away from the critical slope, for example into linear infiltration devices at the foot.

Minimum distances from plot boundary and neighbouring land: One key requirement is that infiltration does not cause problems for neighbours. Although regulations may locally specify concrete distances (often, for example, 2 to 5 m from the plot boundary as a general rule), standards mainly emphasise that the designer must adapt minimum distances to local hydrogeological conditions and the characteristics of the infiltration device, so that there are no disputes or damage across the plot boundary. This means:

- Preventing waterlogging of neighbouring buildings: Infiltration on one plot can raise the groundwater level under the neighbouring plot. This would be particularly problematic if groundwater rose above the foundation level of the neighbour’s house—the result could be damp basements or even foundation damage. To prevent this, the infiltration device must be set back far enough from the boundary so that the influence area of infiltration ends within the investor’s plot. In general, the wetting cone of soil under a point infiltration device can be imagined: water spreads downwards and sideways at about a 45° angle. So, if the infiltration pit is 2 m deep, water underground can reach about 2 m away in all directions. Hence the rule that the distance to the neighbour’s boundary should be greater than the depth of the infiltration device, unless there is an impermeable barrier or similar between them. For linear infiltration trenches (elongated shape), water spreads in the shape of a prism—if the longer side of the trench is parallel to the neighbouring plot, a sufficient strip of dry land to the boundary must also be ensured.

- Mutual influence of several infiltration devices: In densely built-up areas, it can happen that two neighbouring plots each have their own infiltration device close to the shared boundary. If they are too close, their influence cones can overlap and water accumulates in a smaller area, increasing the risk of waterlogging. Therefore, the minimum distance between two infiltration devices (on the same or neighbouring plots) should be at least such that the effects do not add up excessively. In practice, the location of devices is often coordinated between neighbours, or instead of two separate devices, one shared infiltration device is arranged, sized for both areas, and then set further from boundaries and structures. Such an arrangement requires agreement between the owners.
- Protection against erosion and landslides on neighbouring land: If the terrain borders a neighbouring plot at a lower elevation (for example, if the neighbour has land below or is right next to a steep slope, the infiltration device on our plot must be distant enough from the edge so that infiltrated water does not flow out of the slope or weaken slope stability. The safe distance from the top of the slope depends on the amount of infiltrated water relative to natural infiltration. On sloping terrain, the usual rule is: only as much water is led into the infiltration device as would naturally infiltrate there, and the rest (in extreme rainfall) is preferably drained away from the slope. This way, the soil under the infiltration device will not become wetter than it is used to, and new springs will not be created on the slope. The general rule is: the more sensitive the terrain (steeper slope, less permeable lower layer, proximity to springs), the more conservatively minimum distances should be determined and perhaps the proportion of infiltrated water limited.
- Restriction near water sources: If there is a well, spring, or water protection area nearby, the infiltration device must be far enough away not to pose a risk to water quality. Standards recommend, if there is no specific local regulation, at least 30 m safety distance from the infiltration point to the nearest drinking water abstraction. The exact required distance may be greater, depending on soil permeability and groundwater velocity; in water protection zones, it is often required to calculate the so-called 50-day retention time (the distance groundwater travels in 50 days to the abstraction). If the infiltration device is closer than this calculated distance, it is considered not to meet the requirements for protecting the drinking water source. In the context of setbacks from plot boundaries, this means that infiltration must not reach neighbouring plots where, for example, wells are located—this is avoided by correctly positioning the infiltration device away from such points or by installing sealed systems that discharge water deeper and downstream from the source.

B. EVIDENCE OF INFILTRATION SYSTEMS

4. DATA MANAGEMENT AND PROCESSING

The purpose of keeping records of infiltration systems is:

1. To improve incentives for infiltration and reduce the load on the sewer system,
2. To monitor the actual loads on the sewer system, and
3. To enable verification of the proper functioning of devices.

- Improving incentives for infiltration:

Keeping records of infiltration systems is important for monitoring the effects of existing incentives for infiltration and for planning new ones.

The most important and basic incentive for infiltration is the provision that infiltration is the preferred method of drainage wherever possible, and drainage into the sewer system is the last resort when other options are not feasible.

The next most important incentive is the condition that stormwater drainage is only possible into the stormwater sewer, and is limited by the capacity of that sewer. Drainage into a combined sewer is only possible exceptionally, determined on a case-by-case or area-by-area basis.

Financial incentives or subsidies for infiltration, stormwater retention, and disconnection from the sewer system are based on a comparative cost–benefit analysis related to the rehabilitation, upgrading, or construction of sewer infrastructure at the community level, compared with investments in decentralized drainage solutions. In this context, costs associated with wastewater overflows into rivers or the environment, as well as inflows to and discharges from wastewater treatment plants, are also taken into account.

Monitoring the effects of these measures enables the adjustment of incentives with more detailed guidelines and requirements. These may include priority areas or technical criteria for determining limits on permitted discharge, overflow, choice of rainfall event, and safety factor.

Infiltration of roof water on well-permeable soils ($k > 1 \times 10^{-4}$ m/s) should be most strongly encouraged, as roof water in such areas can mostly be infiltrated into the subsoil with only minor retention and without special treatment, except for natural processes. Areas of open traffic surfaces require a larger infiltration area through biologically active soil or another equivalent treatment process.

- Processing data from the records:

  The evidence of infiltration systems can be established:

  a. From expert bases for the preparation of spatial planning acts,
  b. From project data for obtaining connection consent,
  c. From project data for obtaining water consent in the process of obtaining a building permit.

Drainage planning follows a process systematically illustrated from all aspects by the example of the scheme in Figure 13, adapted from the ASIC (Association Suisse infrastructures communales) website, where a flowchart is available that guides the process of stormwater drainage planning.

4.1. Flowchart of the construction project: stormwater drainage planning

For effective planning and implementation of sustainable stormwater drainage measures, it is crucial that the processes of planning, decision-making, and execution are managed according to a clearly defined sequence. For this purpose, a construction project flowchart was used within the project, systematically presenting all key steps in the planning of retention-infiltration systems.

The flowchart (Figure 13) is based on best practice from the Swiss Association for Municipal Infrastructure (ASIC) and has been adapted for use in Slovenian and Croatian urban environments.

The diagram includes the following phases:

- Collection of input data: includes data on contributing areas, geological characteristics of the soil, groundwater level, existing infrastructure, and spatial constraints.
- Determination of boundary conditions: selection of the design rainfall event, determination of permissible discharge (Q_{per}), assessment of soil infiltration capacity (k), and consideration of safety factors and local constraints.
- Calculation of required retention volume and infiltration area: based on input data and boundary conditions, a hydraulic calculation is performed to determine the system dimensions.
- Selection of system type: decision between open, buried, or combined systems, depending on spatial possibilities, aesthetic requirements, and maintenance conditions.
- Obtaining consents and permits: includes coordination with the sewerage operator, obtaining water consent, and building permit.
- Implementation and supervision: construction of the system, quality control of execution, and initial operational testing.
- Entry into the record of infiltration systems: after construction is completed, the system is recorded in the municipal database, enabling further monitoring and maintenance.

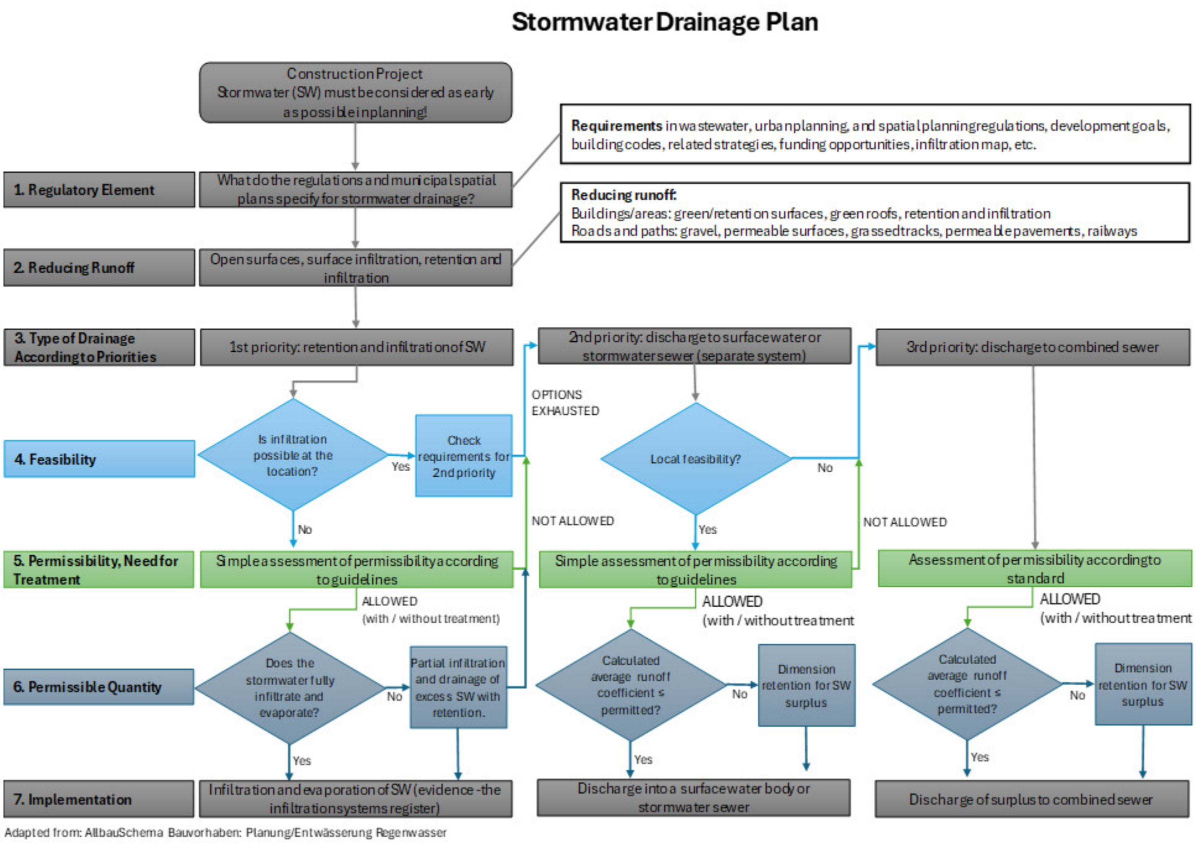


Figure 13. Flowchart of the construction project: stormwater drainage planning (source: ASIC).

This flowchart enables a unified approach to the planning and implementation of measures, which is key to ensuring climate resilience in urban areas. Its use reduces the risk of errors, improves process transparency, and enables better cooperation among all stakeholders involved—from designers and investors to infrastructure operators and municipal authorities.

4.2. Boundary Conditions for the Design of Retention-Infiltration Systems

For the correct design of a retention-infiltration system, it is first necessary to determine the key boundary conditions that limit and guide the planning. These conditions include:

- Design rainfall event – the initial stormwater load is selected, e.g. rainfall of a certain intensity and duration with a given return period (n years) for the area in question. The selected event represents the maximum expected load that the system will still be able to handle.
- Permissible discharge to the public network (Q_{per}) – if part of the stormwater is allowed to be discharged into the sewer, the designer must take this limitation into account. Q_{per} is usually determined by technical guidelines or the consent of the operator; often, the maximum discharge to the sewer (throttle) is set in l/s per hectare. This value represents the capacity of controlled discharge that is still acceptable for the existing network, while excesses must be retained or infiltrated on site.
- Soil permeability and infiltration capacity (k) are determined based on geological investigations and indicate the rate at which the substrate absorbs water (m/s). Together with the available infiltration area (e.g. infiltration field or shaft area), k determines the system's maximum infiltration flow (Q_{inf}). If the measured permeability coefficient at the location is $k = 2.6 \times 10^{-4}$ m/s, about 0.26 l/s of water can infiltrate through 1 m^2 of infiltration area into the ground. Higher permeability and a larger infiltration area mean greater infiltration capacity, which directly affects the required size of the retention tank.
- Local constraints and safety factors – boundary conditions must also take into account possible high groundwater levels, protected water protection areas, restrictions due to the proximity of buildings and infrastructure, etc. (these aspects are discussed in more detail in the section on setbacks). These conditions may limit the depth of infiltration or require additional measures, such as the construction of sealed tanks instead of infiltration in sensitive areas. Safety factors are also determined in calculations, for example, reducing the calculated permeability by a certain factor to ensure the reliability of the system even in the event of unforeseen deviations.
- The listed boundary conditions define the framework within which the calculation and design of the retention-infiltration system take place. When designing a specific system, these parameters must be balanced: if the permissible discharge is small, the system must allow for greater infiltration or retention; if soil permeability is low, a larger retention volume must be provided, etc. A comprehensive consideration of boundary conditions ensures that the final system will safely handle the intended rainfall event and contribute to reducing flood risk and improving water status in the urban environment.

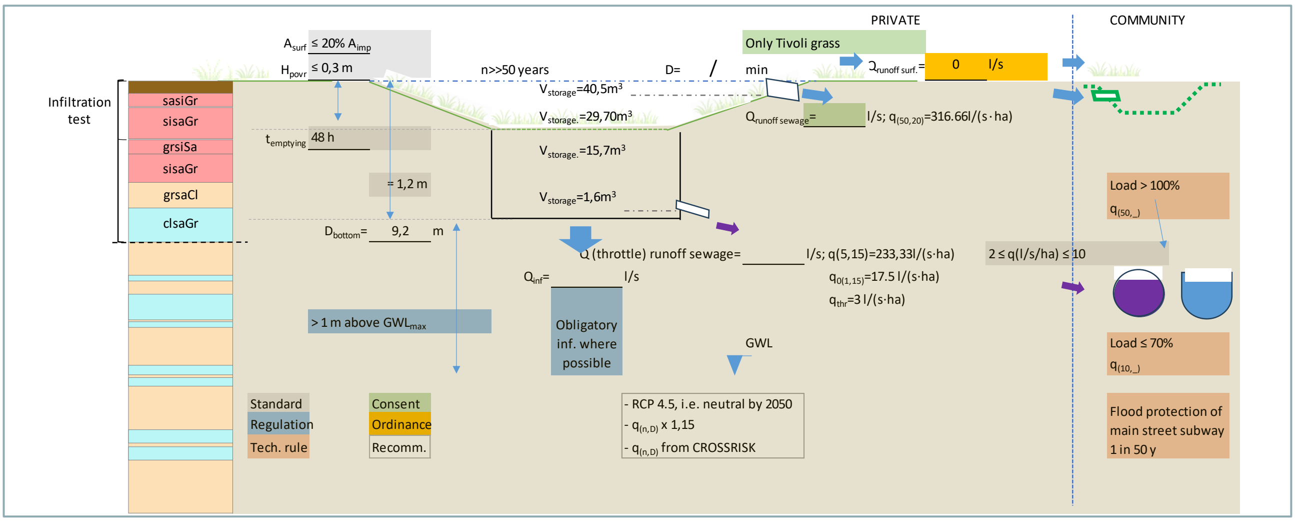


Figure 14. Illustration of types of boundary conditions for the design of retention-infiltration fields.

4.3. Data for the design of retention-infiltration systems

The design of a retention-infiltration system takes place in several steps, using input data on contributing areas and the selected boundary conditions (see Section 4.2). The calculation methodology is summarised below in three main phases, as also shown in the parameter table (Table 3):

1. General data on areas: First, data on the contributing area (A) from which stormwater drains into the system are collected. This includes the sum of impervious surfaces (A_{imp}, e.g. roofs and asphalt) and pervious surfaces (A_{perv}, e.g. lawns) that belong to the retention-infiltration system. Based on these values, a characteristic average runoff coefficient ($\Psi_{m,s}$) is determined, representing the proportion of precipitation that becomes runoff; initially, it is estimated from the share of impervious surfaces. Next, the reduced contributing area (A_{imp}) is calculated, which accounts for the runoff efficiency of the entire area. In the table, an example is given of a total area of 400 m², of which half is impervious ($A_{imp} \approx 200$ m²) and half pervious (200 m²). These data form the basis for further calculations.

2. Selection of design rainfall and discharge flow: The design rainfall event is determined – in our case, for example, a rainfall with a return period of 2 years (n=2) and a selected duration (e.g. 15 min). For this event, the inflow of stormwater from the reduced area is calculated and it is checked what discharge from the system (Q_{disc}) can be allowed. Here, the Q_{per} limit (if discharge to the sewer is allowed) and the infiltration contribution Q_{inf} (if an infiltration element is included) are taken into account. In the table, there is an example where the permitted discharge to the sewer is Q_{per} = 1 l/s. Since the system also infiltrates water, the infiltration contribution $Q_{inf} \approx 0.008$ l/s is calculated, corresponding to infiltration through the bottom of an excavated infiltration device (dimensions 6 m × 5 m) at the given K. The total controlled discharge Q_{disc} from the system (sewer + infiltration) is thus about 1.01 l/s, meaning that up to 1.01 l/s of water will be safely discharged during the rainfall event (about 1 l/s to the sewer and about 0.01 l/s to the subsoil), and the rest must be retained in the retention tank. In practice, the designer checks different combinations of infiltration area sizes and throttled discharges to achieve the optimal balance between infiltration and discharge, in accordance with local regulations and objectives (e.g. maximising infiltration while respecting the discharge limit).

3. Sizing of retention volume: Based on the stormwater inflow (considering A_{imp}) and the agreed Q_{disc}, the required retention volume of the system is determined. The calculation is based on the difference between the inflow and outflow curves: for the selected rainfall event, the excess stormwater that must be retained so that the discharge does not exceed Q_{disc} is integrated. In the

table, this process is shown indirectly – the specific discharge rate (q_{disc} in mm/min is calculated, which together with the size of the reduced area determines the height of water (Δh) to be retained in the tank. The final result is the required retention volume (V_{max}) that the tank must provide so that water does not overflow during the selected rainfall event. In our case (2-year return period rainfall, A_{imp} ~200 m², Q_{disc} ~1 l/s), the tank should retain the maximum volume of stormwater, calculated as $V_{max} = 1.2 \times 10 \times \Delta h \times A_{imp}$ (where Δh is estimated from the hydrograph). With such a determined volume, a specific retention element can be sized (e.g. the volume of an underground retention reservoir or the size of a retention area on the ground).

Note: In addition to hydraulic sizing, qualitative aspects must also be checked – in the case of infiltration, hazardous substances must not enter the subsoil. If there are large traffic or industrial surfaces, appropriate stormwater treatment (e.g. oil separators or vegetative filters) must be provided before infiltration. A safety factor is also included in the final design for the calculated volume (e.g. +10–20%) to ensure the system operates safely even in the event of silting or somewhat larger rainfall events than the design event.

Table 3. Example of data for the design of retention-infiltration systems.

CALCULATION STEP	VALUE TO BE CALCULATED	ASSUMED OR CALCULATED VALUE	
General data	Total areas (A) $A = A_{imp} + A_{per}$ v m^2 *Note: Total area is the entire contributing area from which water can flow into the system during rainfall – both impermeable and permeable surfaces.*	A [m^2] = *Note: 1 ha = 10 000 m^2*	400
		A_{imp} [m^2] =	200
		A_{per} [m^2] =	200
	Runoff coefficient Ψ_m *Note: See appendix*	$\Psi_{m\ imp}$ =	1
		$\Psi_{m\ per}$ =	0
	Permitted discharge (Q_{per}), if allowed	Q_{per} [l/s] =	1
	Soil permeability (k), if infiltration is planned	k [m/s] =	2.60E-04
1. Selection of rainfall event	Frequency – return period	n [years] =	2
2. Discharge flow	Discharge flow (Q_{disc}):	Q_{disc}[l/s] =	1.01
	a) Value set by regulation	Q_{per} [l/s] =	1
	b) Infiltration:	Q_{inf} [l/s] =	0.0078
	In basin: $Q_{inf} = A_{bottom\ of\ basin} \times k$	Q_{inf} [l/s] =	0
	$A_{bottom\ of\ basin}$ = bottom of the basin area	$A_{bottom\ of\ basin}$ [m^2] =	
	In excavation: $Q_{inf} = a \times b \times k$	Q_{inf} [l/s] =	0.0078
	a = length of excavation	a [m] =	6
	b = width of excavation	b [m] =	5
	In trench: $Q_{inf} = 0{,}5 \times A_{vertical\ walls} \times k$	Q_{inf} [l/s] =	0
	$A_{vertical\ walls}$ = area of vertical walls	$A_{vertical\ walls}$ [m^2] =	
	All units in equations are in m^2. Note: 1 m^3/s = 1000 l/s		
3. Retention	Average runoff coefficient: $\Psi_{m,\ s} = (\Psi_{m,\ imp} \times A_{per} + \Psi_{m,\ imp} \times A_{per})\ /\ A$	$\Psi_{m,\ s}$ =	0.5
	Reduced contributing area: $A_{imp} = \Psi_{m,\ s} \times A$ (A in m^2)	A_{imp} [m^2] =	200
	Specific discharge rate (outflow): $q_{out} = 60\ 000 \times Q_{out}\ /\ A_{imp}$ (Q_{out} v m^3/s in A_{imp} v m^2)	q_{izt} [mm/min] =	0.30
	Maximum retention height (determined from the graph in the appendix)	Δh [mm] =	
	Volume of retained stormwater: $V_{max} = 1{,}2 \times 10 \times \Delta h \times A_{imp}$ (Δh in mm in A_{imp} in ha)	V_{max} [m^3] =	

C. DEFINITION OF CLIMATE RESILIENCE OBJECTIVES

Based on analyses of water and mass balances and the results of public consultation, key objectives have been set to increase the climate resilience of urban drainage and thus protect groundwater. These objectives represent measurable directions towards which city authorities and operators will strive in the future. Despite the different circumstances in Ljubljana and Varaždin, the strategic objectives are shared and include:

- Reducing the amount of pollutants in the water cycle: The focus is on hazardous and other problematic pollutants in groundwater (e.g. nitrates, pesticides, heavy metals, industrial chemicals). The aim is to reduce pollutant surpluses entering the aquifer so that their concentration does not exceed the natural purification capacity of the environment. A regular monitoring programme (monitoring groundwater quality) will record concentration trends; if increases are detected, this will trigger measures (e.g. sewerage improvements, reduced fertiliser use).
- Increasing infiltration of rainwater: The key direction is to manage as much rainwater as possible locally at the point of precipitation, rather than through the sewer system. Specifically, this means increasing the proportion of roofs disconnected from the sewer and redirected to infiltration devices or retention tanks. This reduces both the quantitative problem (retaining more rainwater in the soil instead of in pipes) and the qualitative problem (filtration of water through soil). In Ljubljana, for example, it was identified that about 16% of roofs are in areas with very good infiltration capacity—here, infiltration is most sensibly promoted. At the same time, this objective contributes to maintaining groundwater recharge, as a greater share of precipitation remains in the local water cycle and replenishes the aquifer.
- Implementing the sustainable drainage concept in practice: City authorities should fully integrate climate resilience principles into their spatial plans, strategic documents, and investments. This means that for all new urban developments, appropriate drainage and infiltration of rainwater is planned already at the design stage, and existing systems are upgraded according to the principle of “nature first”. Adoption of the expert document—the concept—into formal frameworks (e.g. as a basis for ordinances or planning guidelines) ensures that these objectives are binding and traceable. Indicators for this objective include, for example, the proportion of areas covered by the sustainable drainage programme, the number of infiltration systems installed per year, etc.

5. EXAMPLE VARAŽDIN

Varaždin has defined a concept for planning and decision-making in urban drainage management and, within the framework of public consultation, has made adjustments through the following actions and documents:

- Conclusion on the Guidelines for Sustainable Stormwater Management in the City of Varaždin, including its framework and directions for future planning and investment activities related to sustainable stormwater management; responsibility is assigned to the Administrative Department for Construction and Municipal Services of the City of Varaždin.

To increase climate resilience of drainage in Varaždin, a warning system has been established to monitor pollutant surpluses and incentives for the development of reuse of roof rainwater and relief of the sewer system.

The city council of Varaždin has adopted a Decision on Guidelines for Sustainable Stormwater Management, which includes a new framework and directions for future drainage arrangements. With this decision, responsibility for managing the implementation of measures has been officially assigned to the city’s

Administrative Department for Construction and Municipal Services. In addition, an early warning system has been established in Varaždin to monitor pollutant surpluses in groundwater, and new financial and technical mechanisms have been introduced to encourage the reuse of collected rainwater (e.g. for irrigation) and relieve the sewer system. These measures increase awareness and readiness for rapid action in the event of deviations (e.g. if monitoring detects a rise in hazardous substance concentrations).

6. EXAMPLE LJUBLJANA

The Ljubljana example has defined a concept for planning and decision-making in urban drainage management and, within the framework of public consultation, has made adjustments through the following actions and documents:

- Presentation for JP VOKA SNAGA employees
- Comments on the draft OPN MOL regarding infiltration and natural terrain, etc.
- Implementation programme for public drainage and treatment services 2025–2028
- Updated Technical regulations for sewerage, JP VOKA SNAGA, EAD-116244, April 2025
- For greater climate resilience of drainage and infiltration in Ljubljana, specific objectives have been set for redirecting roof rainwater from the sewer to infiltration, maintaining groundwater recharge, and reducing surpluses of certain pollutants.

In Ljubljana, the local utility company (JP VOKA SNAGA) has prepared additional internal instructions and training for employees so that the principles of the new concept will be applied in daily work (e.g. when issuing consents, inspecting connections). The city received comments during the public consultation on the preparation of the Municipal Spatial Plan (OPN)—especially regarding mandatory infiltration of rainwater and the preservation of as many natural infiltration areas as possible in the city. These comments are aimed at the goal of climate resilience (e.g. requirement for retention tanks at new car parks, restrictions on connecting roofs to combined sewers, etc.). A series of measures from the concept (from plans for sewer renovation with system separation, introduction of throttles, to the establishment of several new pilot infiltration fields) has also been included in the Implementation Programme for Public Drainage and Treatment Services for the period 2025–2028. With these integrations, the concept is not just a theoretical document, but already part of the municipality’s operational plans.