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## Optimization of urban drainage and resilience of groundwater quality (booklet): Use of the infiltration capacity map (from field investigation to planning, consenting and decision-making)

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| **WP 4** Resilience to climate change impacts on urban groundwater quality through spatial planning elements |
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Note:

The original document was prepared in the Slovenian language. This document represents an English translation provided for the purposes of international cooperation within the Interreg / EU programme. In the event of any ambiguity, discrepancy in interpretation, or doubt regarding the content, the Slovenian language version shall prevail as the reference version.

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Booklet

## USE OF THE INFILTRATION CAPACITY MAP - FROM FIELD INVESTIGATION TO PLANNING, CONSENTING AND DECISION-MAKING

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# List of symbols and notation

$\Delta h$ - Depth of retained water in the infiltration facility (m)
$A$ - Land area ($m^2$)
$A_{imp}$ - Impervious land area ($m^2$)
$A_p$ - Infiltration area or pervious (infiltration) surface ($m^2$)
$D$ - *R*ainfall duration (minutes)
USI - the unsealed surface index
FP_L – The factor of paved living surfaces
FP_T - The factor of paved transport, utilities and technical surfaces
BF - The built-up area factor
$h_{(r.D)}$ - Rainfall depth (mm) with return period r (years) and rainfall duration D (minutes) ($mm/m^2$)
$h_p$ - Depth of infiltrated (runoff) water from the land area ($mm/m^2$)
$i$ - Hydraulic gradient (-)
$I_{r,D}$ - Rainfall intensity (mm/h) with return period r and duration $D$
$k$ - Hydraulic conductivity (m/s)
$n$ - Rainfall frequency (number of occurrences per year ($a^{-1}$))
$q_{(n,\ D)}$ ali $q_{(r,\ D)}$ - Rainfall with a given frequency and duration (l/s/ha)
$q_{(r,D)}$ - Specific inflow from rainfall with return period r (years) and duration $D$ (minutes), i.e. design rainfall intensity (l/s/ha)
$q_0$ - Specific runoff under natural conditions (l/s/ha)
$Q_{dov}$ - Allowable discharge, i.e. the quantity permitted to drain (be discharged or overflow) to the surface, a surface water body, or the sewer system ($m^3/s$)
$Q_{izp}$ - Discharge ($m^3/s$), the amount of stormwater runoff from the land area
$Q_{odt}$ – Total runoff from the land area ($m^3/s$)
$q_{odt}$ – Specific total runoff from the land area (l/s/ha)
$Q_p$ - Infiltration flow rate ($m^3/s$)
$q_p$ - Specific infiltration capacity of the land ($m^3/s/m^2$ = l/s/ha × $10^{-7}$)
$Q_{thr}$ – Throttled discharge or flow through a flow restrictor ($m^3/s$)
$q_{thr}$ - Specific allowable throttled discharge (l/s/ha)
r – Rainfall frequency or return period (number of years ($r$ ($a$)) between such events)
$r_A$ –Ratio between impervious land area and infiltration area, $A_{imp}$ / $A_p$ (-)
$V_p$ - Volume of infiltrated (runoff) water from the land area ($m^3$)
$V_{r,D}$ - Volume of water generated by rainfall with return period $r$ (years) and duration $D$ (minutes) ($m^3$)
$V'_z$ - Specific retention volume ($m^3/m^2$)
$\Psi_0$ – Runoff coefficient under natural conditions
$\Psi_m$ - Mean runoff coefficient

# INTRODUCTION

The booklet Use of the infiltration capacity map - from field investigation to planning, consenting and decision-making comprises four interrelated volumes, labelled A to D. Each volume covers a self-contained set of topics, which are nevertheless inseparably linked for understanding the concept and significance of Infiltration capacity maps.

Volume A discusses the role and importance of infiltration in modern urban stormwater drainage.

Volume B explains how to design and prepare a soil infiltration capacity map.

Volume C presents selected practical examples of using infiltration capacity maps in planning.

Volume D provides practical guidance for a more detailed assessment of soil permeability at the locations of proposed interventions.

# A. THE ROLE OF INFILTRATION IN STORMWATER DRAINAGE

## 1. Infiltration in modern stormwater management

### 1.1. Modern approaches to stormwater management

Modern approaches to stormwater management in cities increasingly follow a concept referred to in professional hydrotechnical literature and on official public authority websites as the "permeable city" (e.g. Lyon, Rotterdam) or the "sponge city" (e.g. Berlin, Milan, Copenhagen).

A permeable city enables water to flow without significant ponding or concentration of water volumes and mass flows. Preventing the concentration of water volumes and mass flows is achieved by limiting increases in surface runoff and avoiding the overloading of natural drainage paths and artificial conveyance systems. This approach begins in the city's hinterland, in agricultural and forested areas, and continues through the urban fringe towards the city core. Prescribed buffer distances and widths of riparian land are maintained. Space is provided for water spreading and drainage during extreme rainfall events. Riparian areas are reserved for basic flood protection, specifically for regulating retention capacity and the infiltration of surface water into the subsurface.

Spatial planning based on the "sponge city" concept (Griffiths et al., 2020) is inspired by the properties of a sponge, which absorbs, retains, purifies, and gradually releases water. The main characteristics of stormwater management under the "sponge city" approach include maintaining soil permeability and infiltration, retaining rainfall in surface depressions, using the subsurface to store runoff during heavy rainfall, retaining or diluting substances from urban discharges, and seasonally storing groundwater reserves for use during drought.

The entire functional urban area should comprise less than 3% built-up surfaces. Spatial arrangements within planning units should aim to achieve the lowest possible runoff coefficient, with a mean runoff coefficient $\Psi_m < 0.6$, optimally approaching $\Psi_m \approx 0.3$. A lower proportion of impervious surfaces increases infiltration potential and improves overall stormwater runoff management.

Promoting stormwater infiltration in urban areas is becoming increasingly important, primarily because it relieves discharges from paved surfaces into sewer systems or surface waters and helps prevent flood events.

Infiltration is a key element of stormwater management and is essential for maintaining the natural renewability of groundwater resources. However, as infiltration capacity depends on natural soil conditions and other environmental constraints, the preparation of guidelines and infiltration capacity maps at the local level is necessary. These maps help identify and delineate areas according to their infiltration capacity, thereby facilitating integrated drainage planning within spatial development processes.

Infiltration capacity is an important land characteristic that must be considered to optimally support:

- sizing of blue-green infrastructure and nature-based solutions (sponge city),
- integration of regulatory elements (climate change resilience),
- reducing surface runoff and relieve the public sewerage system,
- seasonal storage of groundwater (availability of natural resources),
- maintenance of the natural retention capacity of aquifers (circular economy).

## 1.2. Standards, guidelines and recommendations

Planning for infiltration requires familiarity with a range of standards that incorporate existing knowledge and experience in drainage design, including infiltration as part of stormwater management. Regarding infiltration, the standards address the following key issues:

- how to ensure the long-term reliable performance of infiltration facilities,
- how to size the infiltration surface and retention volume to reduce peak runoff,
- how to treat water so that it is suitable for infiltration into the subsurface,
- how to define minimum setback distances from plot boundaries and neighbouring structures,
- what solutions are available where infiltration capacity is low or negligible.

The standards provide various approaches, solutions, and recommendations. They are primarily adapted to local legislation and regulatory frameworks, but generally pursue the same objectives: to manage stormwater appropriately and as practically as possible on one's own land, without causing damage to one's own or neighbouring properties, and in a cost-effective manner.

Modern standards include solutions that facilitate the implementation of infiltration while considering pollutant loads in stormwater and the capacity of soils to retain pollutants. This supports the achievement of adequate wastewater quality and creates favourable conditions for the development of a circular economy. This chapter highlights selected standards and recommendations most frequently used in the preparation of this handbook.

ATV - A 128E: Standards for the dimensioning and design of stormwater structures in combined sewers (1992)

CIRIA C753: The SuDS Manual (2015)

CIRIA C768: Guidance on the Construction of SuDS (2017)

CIRIA Report R156: Infiltration drainage – Manual of good practice (1996)

DWA-A 138E: Planning, construction and operation of facilities for the percolation of precipitation water (2005)

DWA-M 153E: Advisory leaflet DWA-M 153E: Recommended actions for dealing with stormwater (2007)

DWA-A 117E: Bemessung von Regenrückhalteräumen (2013)

DWA-A 100E: Leitlinien der integralen Siedlungsentwässerung (ISiE) (2006)

SIST EN ISO 14688-1:2004: Geotechnical investigation and testing – Identification and classification of soil – Part 1: Identification and description (ISO 14688-1:2002)

SIST EN ISO 14688-2:2004: Geotechnical investigation and testing – Identification and classification of soil – Part 2: Principles for classification (ISO 14688-2:2002)

SIST-TP CEN/TR 12566-5:2006: Filtration units for pre-treated domestic wastewater. Small wastewater treatment systems up to 50 PE (2006)

SIST-TP CEN/TR 12566-2:2006: Soil infiltration systems. Small wastewater treatment systems up to 50 PE (2006)

SNV SN 592 000:2024: Installations pour l'évacuation des eaux des biens-fonds (2024)

VSA: Gestion des eaux urbaines par temps de pluie. Envoi complet (2019)

Publications:

Aqua Urbanica (2022). Proceedings of the Aqua Urbanica 2022 Conference: Sustainable water management in urban areas. Austrian Association for Water Management (ÖWAV) and German Association for Water, Wastewater and Waste (DWA).

VÍTEK, Jiří, STRÁNSKÝ, David, KABELKOVÁ, Ivana, BAREŠ, Vojtěch and VÍTEK, Radim. Rainwater Management in the Czech Republic. Prague: 01/71 ZO ČSOP Koniklec, 2015. ISBN 978-80-260-7815-9.

CTU in Prague, Faculty of Civil Engineering. Standards for Rainwater Management in Prague. Authors: Stránský, David, Hora, David, Kabelková, Ivana, Vacková, Michaela, Vítek, Jiří. Prague: City of Prague, 2016.

WATER IN THE CITY. Methodology for Rainwater Management Linked to Green Infrastructure. Prague: CTU, 2018. ISBN 978-80-01-06817-5.

## 1.3. Key elements of drainage

The key elements of stormwater drainage are runoff control, retention, discharge, and overflow (Figure 1).

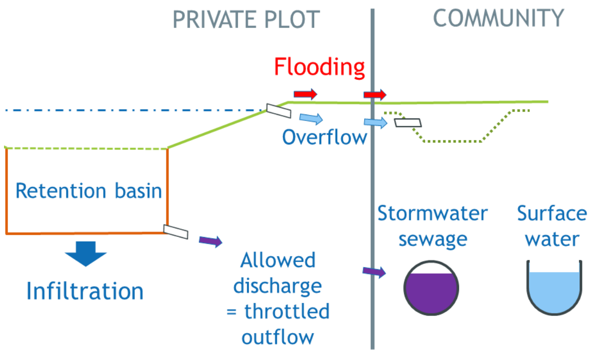



*Figure 1. Key elements of drainage.*

Surface runoff is determined by the degree of surface sealing or permeability, slope, and antecedent soil moisture, while other elements are also regulated through infiltration.

Retention can be achieved in various ways, including surface depressions, basins, or subsurface backfilled trenches.

Discharge may occur into the soil and groundwater through infiltration, into a surface watercourse, or into the sewer system.

Overflow can be discharged by spreading over the terrain or into a surface watercourse, in accordance with the conditions set by the operator. As a rule, overflows are not permitted to be discharged into the public sewer system.

Infiltration is limited by infiltration capacity, which primarily depends on permeability and several other factors.

Drainage into a surface watercourse or the sewer system is limited by their respective capacities.

Permits for the location and quantity of water discharged into the sewer system or surface watercourse are issued by the operators or competent authorities.

- Runoff

Under natural conditions, before any interventions, natural runoff occurs from the land area $A$ ($m^2$). Interventions and developments alter the mean runoff coefficient of the land ($\Psi_m$) and, consequently, the surface runoff $Q_{odt}$ ($m^3/s$) during rainfall events.

Rainfall is the amount of precipitation falling per unit area during a rainfall duration *D* (minutes) and is defined by its frequency (*n* ($a^{-1}$)), i.e. how many times per year such an event occurs, or by its return period (*r* (*a*)), i.e. how often such rainfall events recur, expressed as $q_{(n,\ D)}$ or $q_{(r,\ D)}$ (l/s/ha).

Runoff from land is controlled by choosing solutions that minimise surface sealing. An example of determining surface runoff using the so-called Rational method:

$$A_{imp} = A \times \Psi_m \quad (1)$$

$$Q_{odt} = q_{(r,D)} \times A_{imp} = q_{(r,D)} \times A \times \Psi_m \quad (2)$$

where $A_{imp}$ is the effective impervious area and $q_{(r,D)}$ is the specific rainfall flow (design rainfall intensity).

Planning interventions that minimise surface sealing reduce the complexity and extent of measures required to protect people and property from flooding. At the same time, they preserve as much water as possible within the natural water cycle.

- Retention

Retention of stormwater runoff from a land area is required to reduce peak flows. If the peak flow is reduced to a level that does not exceed the pre-development peak flow, the impact on the runoff regime will be relatively small. In this way, the intervention can be considered acceptable, as it will not lead to increased erosion or overloading of the sewer system or drainage channel.

- Infiltration

Infiltration is the percolation of water into permeable soils. The infiltration flow rate $Q_p$ ($m^3/s$) depends on the soil permeability coefficient *k* (m/s), the infiltration area $A_p$ ($m^2$), and the hydraulic gradient (*i*), or alternatively on the depth of retained water in the infiltration facility $\Delta h$ (cm).

- Discharge

Discharge $Q_{izp}$ ($m^3/s$) is the amount of stormwater that drains from the land area to:

- the environment (overland flow),
- a surface water body (ditch, stream, river, lake, sea),
- the sewer system (stormwater or combined sewer).

The allowable discharge $Q_{dov}$ ($m^3/s$), or throttled outflow, is the quantity permitted to be discharged to the surface, a surface water body, or the sewer system.

  - Discharge to the environment – overland flow

Overland discharge is limited by the surface over which the water flows until it infiltrates into the soil. Peak runoff during rainfall events should not exceed the natural runoff from the land area designated for drainage. This must not result in erosion, washing out of organic matter, increased runoff onto neighbouring land, or flow towards adjacent properties.

  - Discharge to a surface water body

Discharge to a surface water body is limited by its hydraulic capacity. Peak flow into the receiving water should not exceed the natural peak flow if deterioration of erosion and flood risk conditions is to be avoided.

A higher allowable discharge may be permitted if verified by a hydrological-hydraulic assessment, or a lower discharge may be required where higher safety levels are needed.

  - Discharge to the sewer system

Discharge into a stormwater sewer is generally permitted only up to a specified limit, determined by the capacity of the sewer system. The sewer capacity is typically designed so that the combined stormwater discharges from the contributing catchment to an individual sewer section, under the planned final spatial development, do not exceed a defined capacity, for example, up to 70% pipe filling during a rainfall event with a specified return period. The capacity is defined and controlled by the system operator. The return period is determined by safety requirements based on the sensitivity of the area, for example once every 10 years ($n = 0.1\ a^{-1}$) for traffic-related underground structures or underpasses (according to SIST EN 752-2).

Discharges of stormwater into combined sewers are treated differently. Such discharges are allowed only exceptionally; therefore, permitted quantities may be lower or limited to a minimum sufficient to allow at least slow emptying of retention facilities.

- Overflow

Overflow is the discharge of water during extreme rainfall events that exceed the design safety level of retention, infiltration, or allowable discharge.

With permission, overflow may be directed partially or entirely to controlled overland flow, into a drainage channel, or to designated overflow, retention, or infiltration areas. Discharge of overflow into the sewer system is generally not permitted.

Flooding during more extreme rainfall events should occur with a frequency of once every 30 years or more ($n \leq 1/30\ a^{-1}$, $r \geq 30$ a), depending on the type of settlement and the infrastructure present in the area.

In areas with good soil and groundwater permeability, infiltration may also be used to convey all or at least part of the overflow.

# 2. Review of good practices in infiltration capacity mapping

## 2.1. Experiences and applications of infiltration capacity maps in selected countries

The first review of existing guidelines for the feasibility of infiltration systems was prepared in 2016 (Gerolin et al., 2016). The authors found that specific instructions and guidelines are available in national documents (ARSIT, 1995; Barraud et al., 2009; Cerema and DGALN, 2014; DWA, 2005) or more generally in stormwater management guidelines (DWA, 2007; MDDEFP, 2014; SIA, 2012; VSA, 2002; Woods-Ballard et al., 2007). Local communities often formulate their own instructions, but most of these recommendations do not include specific guidelines for creating infiltration capacity maps (rainwater infiltration potential) (Gerolin et al., 2016).

In 2016, Gerolin and colleagues (Gerolin et al., 2016) collected and analysed 22 different "Infiltration Capacity Maps" from various parts of the world and compared them based on terminology used, starting points, and objectives. In this document, we compare selected existing studies in terms of the categories and criteria applied for preparing infiltration capacity maps. These maps are generally intended for informational purposes, strategic planning, and preliminary assessment of the feasibility of construction projects. In most cases, additional field investigations are required for construction projects, except in areas with poor infiltration capacity (Dearden, 2016; État de Genève, 2005; Gerolin et al., 2016). International examples of infiltration capacity maps often rely on various decision-making schemes that address natural predispositions for infiltration, such as soil permeability or water balance assessments, groundwater vulnerability, and potential risks based on soil type and land use.

- Switzerland (État de Genève, 2005; Gerolin et al., 2016)

Categories (3): 1. good infiltration potential, 2. potential to be determined individually, and 3. poor potential or infiltration prohibited

Criteria: soil permeability; depth to groundwater; thickness of surface deposits; soil stability; contaminated soils; quarries; springs; wells.

- United Kingdom (Dearden, 2016)

Categories (4): 1. highly compatible with infiltration-based sustainable drainage systems, 2. likely compatible with infiltration-based sustainable drainage systems, 3. opportunities for adapted infiltration-based sustainable drainage systems, 4. very specific constraints e.g. - depth to groundwater, thickness of deposits above the impermeable layer.

Criteria: permeability of deposits and substrate; limitations related to artificial embankments and/or contaminated soil; limitations due to soil instability (landslides, rocks/sediments prone to dissolution and subsidence); limitations related to shallow mining; limitations related to floodplain material; environmental and water protection zones; dominant flow mechanism (intergranular, fissure).

- Czech Republic (Hradec Králové) (Suchanek et al., 2013)

Categories (4) for rainwater infiltration (storm events): 1. no restrictions, 2. conditionally suitable, 3. Difficult, 4. not possible

Criteria: location and function of the building; contaminated areas; soil slope; ownership of infiltration area and surroundings (public/private); availability of space and presence of areas suitable for rainwater infiltration.

- USA (Sonoma Valley) (SEC and SCWA, 2011)

Categories (6): Infiltration potential based on geology: 1. Poor, 2. poor to moderate, 3. Moderate, 4. moderate to good, 5. Good, 6. good to very good.

Criteria (7): Infiltration potential: classification into seven natural classes using Jenks methodology, which groups data to minimise within-group variance and maximise between-group variance. Four-element model with weights: vegetation (10%); soil type (25%); geology (50%); slope (15%).

Constraints: impervious surfaces; protected areas; vineyards; shallow groundwater.

- France (Hauts-de-Seine) (Hauts de Seine, 2011)

Categories (9): 1. mostly permeable soils: infiltration generally possible, 2. generally permeable soils with possible less permeable zones: infiltration generally possible, 3. terrain with >10% slope: infiltration not recommended, 4. possible presence of gypsum: expert assessment required, 5. possible presence of swelling clays (high to medium risk): expert assessment required, 6. possible presence of gypsum and swelling clays (high to medium risk): expert assessments required, 7. water catchment protection zones: infiltration prohibited, 8. possible presence of old quarries: consultation with Geological and Mining Institute required, 9. contaminated soil areas (May 2009): safety zone with 50 m radius: check regulatory restrictions

Criteria: soil permeability; temporary or permanent soil moisture; terrain slope; presence of gypsum and swelling clays in soil or subsoil and presence of cavities; proximity to groundwater; water supply protection zones; proximity to contaminated or potentially contaminated areas and soils, including risk of pollutant migration into soil and subsoil.

- France (Nantes) (Nantes Métropole, 2022)

Categories (3): 1. green zone – "favourable": the location generally presents few or no restrictions for rainwater infiltration. A soil study should confirm the ease of implementing infiltration solutions. 2. yellow zone – "moderately favourable": infiltration is likely possible. Some constraints may require additional investigations to adapt and optimise infiltration solutions. 3. red zone – "unfavourable": certain constraints are likely to require detailed investigations for a local feasibility assessment of infiltration solutions. Results may lead to considering regulated discharge alongside infiltration. Even with low infiltration capacity, light rainfall can still be infiltrated.

Criteria: soil type; depth to groundwater; network development and persistence index reflecting the soil's ability to transmit rainfall.

The Nantes example is particularly interesting because, in addition to a suitability map for infiltration, a map was prepared showing priority areas defined by minimum criteria for infiltration and water retention. For each area, minimum water volumes to be retained on-site through infiltration, rainfall return periods (10–50 years), and maximum allowable runoff rates (3 or 10 l/s) are specified. Areas are primarily divided by ownership type – individual properties or business/public buildings, blocks, and car parks.

Areas of individual properties are divided into two zones: 1. unified zone, where no specific regulations apply. 2. other development areas, where infiltration of at least 16 litres of water per m² of impervious surface must be ensured, with runoff limited to 3 l/s.

Areas of other properties (commercial or public buildings, apartment blocks, car parks, etc.) are divided into four zones:

1. Main priority production area: infiltration of at least 16 litres per m² of impervious surface, retention of rainfall with a 50-year return period, runoff limited to 3 l/s/ha.
2. Secondary priority production area: same infiltration requirement, retention for a 30-year return period, runoff limited to 3 l/s/ha.
3. Non-priority production area: same infiltration requirement, retention for a 10-year return period, runoff limited to 3 l/s/ha.
4. Unified area: infiltration of at least 6 litres per m² of impervious surface, retention for a 10-year return period, runoff limited to 10 l/s/ha.

To assist designers, Nantes Métropole also produced a synthesis map of soil potential for rainwater infiltration, considering soil type, depth to groundwater, and network development and persistence index. Areas are classified into three suitability classes:

- Green zone, "favourable": few or no restrictions; a soil study should confirm feasibility.
- Yellow zone, "moderately favourable": infiltration is likely possible; some constraints may require further investigation.
- Red zone, "unfavourable": constraints are likely to require detailed investigations; regulated discharge may be considered alongside infiltration. Even with low infiltration capacity, light rainfall can still be infiltrated.

The map also includes important information to consider for infiltration, such as the presence of drinking water catchments or steep slopes. As part of soil investigations, other highly localised factors not shown on the map should be analysed, such as geotechnical risks or contaminated soils.

If specific restrictions apply to a location, detailed investigations are needed to verify constraints and assess under what conditions infiltration solutions can be implemented.

## 2.2. General recommendations and guidelines

On-site wastewater management is the **responsibility of the landowner** (Nantes Métropole, 2020).

The landowner must adapt the drainage system to the type of project, site topography, and the characteristics of the soil and subsoil to ensure proper collection, treatment, retention, and discharge of wastewater, in accordance with the requirements of local or national legislation.

For sound and sustainable wastewater management in urban areas, it is necessary to:

1. avoid unnecessary soil sealing wherever possible;
2. reduce soil sealing by selecting permeable materials for parking areas, paths, and pavements, and by using green roofs on buildings;
3. aim to infiltrate as much rainfall as possible, so that the smallest possible amount is discharged onto other land parcels or into drainage channels;
4. discharge stormwater into sewer networks and public systems only as a last resort;
5. compensate for surfaces that have had to be unavoidably sealed.

## 2.3. Decision-making for infiltration

Key questions before introducing infiltration (Dearden, 2016):

- **What is the infiltration capacity?**

  This step provides information on the depth to groundwater, permeability and moisture of surface layers and the saturated zone, permeability of the bedrock, type of vegetation, and soil slope.

- **Are there concerns regarding soil stability?**

  Consider hazards such as the presence or proximity of landslides, soils prone to settlement or shrinkage (silts and clays), quicksand, shallow mining, and rocks susceptible to dissolution (various types of salts, including carbonates).

- **Could infiltration cause deterioration of groundwater quality?**

  Local regulations for water resource protection must be considered (e.g., possible restrictions in water protection zones), as well as the potential presence of contaminated soil, either in its natural state or as artificial embankments.

# B. PREPARATION OF THE INFILTRATION CAPACITY MAP

*The preparation of a map depends on its intended purpose, the local hydrogeological conditions within the functional urban area, and the prevailing climatic conditions.*

*In most cases, the aim is for the map to serve the widest possible range of applications. However, there is usually one primary initial motivation that guides its development.*

*It is therefore important to consider which existing maps – geological or hydrogeological – are already available for the area and which datasets from previous investigations can be used.*

*Climate can also be a decisive factor in map design. Differences in climatic characteristics may result in significantly different infiltration capacities, particularly in urban areas with high or low rainfall intensities, where the differences may be several-fold.*

*For this reason, the first step is to define the range of possible uses for the map, followed by the range of hydrogeological characteristics, and finally the intensity of rainfall and the surplus stormwater volumes that need to be managed or discharged.*

| Chapter 3 | Chapter 4 | Chapter 5 |
|---|---|---|
| Purpose of use | Local hydrogeological conditions | Local climatic conditions |

## 3. Adapting the map to its intended use

The infiltration capacity map shows the spatial distribution of subsurface potential for stormwater infiltration at the urban area scale.

The infiltration capacity map may be used for one or more of the following purposes:

- strategic spatial planning;
- detailed spatial planning for implementation;
- preliminary feasibility assessment of infiltration during the design phase;
- support in obtaining project conditions;
- assessment of site suitability for infiltration during the consent process.

The key elements of drainage (Chapter 1.3) indicate that the main question is what proportion of excess rainfall generated on a parcel can be infiltrated. The primary concern is whether, for the planned stormwater management measures, overflows and discharges to neighbouring parcels, public areas, or the public drainage network will be required. Subsequently, the required surface area and storage volume on the parcel for water retention prior to discharge, overflow, or infiltration are assessed.

These questions arise at the stage of initiating the preparation of a spatial planning document (for planned developments or changes in land use) and are then addressed in greater detail during the design and optimisation of solutions for obtaining consents and permits.

# 4. Adaptation of the map to local hydrogeological conditions

## 4.1. Map of overlaying strata

Rainwater generally infiltrates into the upper geological layers above the groundwater table. Most constructions are shallower than 15 m, or up to five basement levels. Most geomechanical investigations are conducted to this depth. The majority of geotechnical reports cover terrain up to 5 m deep, with significantly fewer extending beyond 10 m. From this perspective, the infiltration capacity map is most relevant for depths up to 15 m.

In addition to the term “upper layers” (overlying strata), the term “cover layers” is also used. It is important to note that both terms can have specific and different meanings. “Upper layers” refers to geological strata developed from the surface to a certain depth, for example, to the groundwater level or, in this case, to a depth of 15 m. “Cover layers” is often used in a hydrodynamic sense to describe less permeable layers that cover an aquifer and give it a specific hydrodynamic character, such as confined, semi-confined, or semi-unconfined aquifers. Therefore, “cover layers” is frequently used to describe aquifer and groundwater vulnerability to contamination.

To prepare the infiltration capacity map, we use available spatial and field data that allow assessment of soil permeability, focusing on the upper 15 m below the surface:

- Existing maps of upper or cover layers and groundwater levels (if available)
- Geological and hydrogeological data from borehole logs (soil composition, presence of low-permeability layers, depth to the groundwater, and depth to the impermeable bedrock)
- Results of permeability measurements (infiltration and percolation tests within the upper 15 m of soil)
- Data from granulometric analyses of soil samples down to 15 m depth

## 4.2. Assessment of upper layer permeability

The most reliable basis for assessing upper layer permeability is geotechnical reports that describe upper layers in accordance with the standard for soil identification and classification (e.g., SIST EN ISO 14688:2004) (i.e., geotechnical logging). In urban areas, there is sufficient data of this type to allow statistically significant analyses. The more consistently standard geotechnical logging is applied during investigations, the more useful these data are for permeability assessment.

Among the many standard descriptions of soil samples taken during geotechnical investigations in a given area, only a smaller proportion includes granulometric analyses. Samples with available granulometric analysis results are used to estimate permeability using established granulometric methods.

Granulometric curve analysis often includes calculating the hydraulic conductivity (*k*) using the USBR and/or Hazen methods, which are based on grain size distribution and ratios between sediment fractions (Equations 1 and 2; Urumović et al., 2020):

$$k_{USBR} = 0{,}36 \cdot {d_{20}}^{2{,}3} \qquad (3)$$

$$k_{Hazen} = 1{,}0 \cdot {d_{10}}^{2} \qquad (4)$$

where *k* is hydraulic conductivity according to the USBR or Hazen method, expressed in cm/s; $d_{10}$ and $d_{20}$ are the grain size diameters (mm) at which 10 or 20 % of the sample’s mass, respectively, are comprised of particles with a diameter less than this value.

The variability of these calculated hydraulic conductivity values, and occasional large deviations from actual permeability, are relatively high for several reasons:

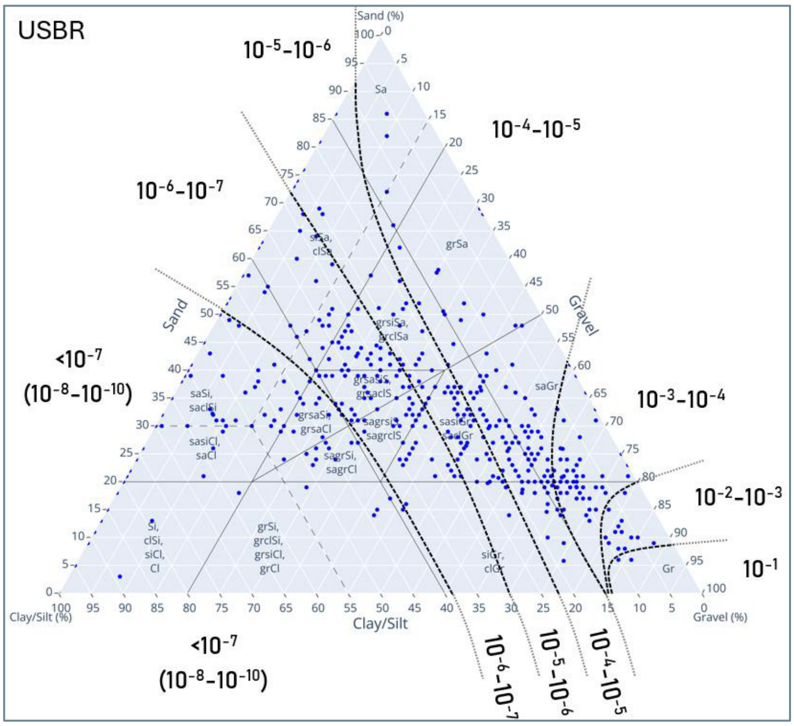
- the methods are more or less suitable for specific sediment types and depositional conditions,
- samples are not randomly selected for permeability analysis but are mostly chosen for stability and foundation purposes,
- samples represent a thin layer within the upper strata,
- uniformity, sorting, compaction, and grain shape vary greatly,
- core quality from boreholes is highly variable.

Therefore, a single granulometric analysis of a sample from a specific depth or location has very limited applicability for the design of retention and infiltration systems unless it is integrated into a comprehensive geotechnical and hydrogeological site assessment. Only a combination of multiple granulometric analyses with other types of investigations enables a reliable estimate for designing infiltration and stormwater retention systems.

Some studies (e.g., Urumović et al., 2020) and standards (e.g., DWA-A138E, p. 57) propose certain corrections to hydraulic conductivity values obtained by different methods. However, these corrections are valid only for specific areas or conditions.

Only with a larger number of samples from the urban area containing grain size distribution data can a statistical analysis be performed to define characteristic proportions of sediment fractions and their relationship to permeability ranges (Figure 2, Figure 3).

Geotechnical classifications of soil samples are highly variable due to changes in standards and inconsistencies among loggers. Available logs need to be checked and corrected where deviations from standard descriptions can be reliably identified. For example, the description “gravelly sandy soil” can be replaced with the standard description “gravelly sand (grSa)” if this is evident from granulometric composition or other information (e.g., typical profiles).




Legend

*k* (m/s)

percentage of clay / silt / sand

Sand – Sa – sand

Gravel – Gr – gravel

Clay – Cl – clay

Silt – Si – silt

*Figure 2. Overview of samples with measured grain-size distributions and estimated hydraulic conductivity coefficient (k) values calculated using the empirical USBR equation (Ljubljana case study).*

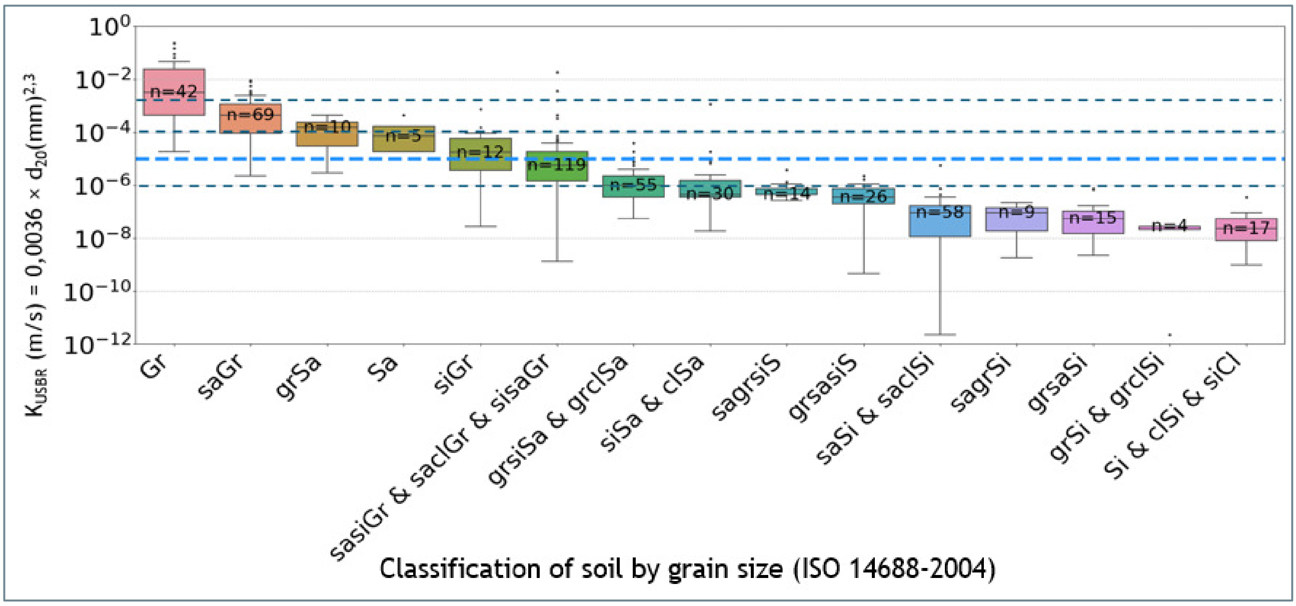



*Figure 3. Box-Whisker plot of the USBR permeability coefficient (k) for different grain-size categories of sediments in the Ljubljana area (n = 496). The graph shows the median and range of the permeability coefficient.*

The estimated hydraulic conductivity coefficients, calculated using Equations (3) and (4), are classified into soil groups according to their geotechnical descriptions. This comparison reveals the permeability ranges for different grain-size composition categories, depending on the selected empirical determination method (e.g. Equation 3 or 4).

By applying statistical analysis to the permeabilities calculated using Equations (1) and (2), together with the standard geotechnical descriptions of the samples (Figure 3), it is possible to estimate the permeability of samples for which grain-size composition has not been determined and only a geotechnical description is available. The reliability of the predicted hydraulic conductivity coefficients for these samples is lower than for samples with a determined grain-size composition.

The example of Ljubljana shows that characteristic differences in calculated permeabilities occur in the median and quartile values Q1 and Q3 (Figure 3) among the key soil groups. Soils classified as gravel (Gr) and sandy gravel (saGr) can be expected to have permeabilities of $k > 1 \times 10^{-4}$ m/s. Soils classified as gravelly sand (grSa), sand (Sa), and silty gravel (siGr) typically exhibit permeabilities in the range of approximately $k \approx 1 \times 10^{-4}$ m/s to $k \approx 1 \times 10^{-5}$ m/s. For soils classified as sands with 20–30% fine-grained fraction, permeabilities can be expected in the range of $k \approx 1 \times 10^{-5}$ m/s to $k \approx 1 \times 10^{-6}$ m/s. For soils dominated by silt, permeabilities below $k < 1 \times 10^{-6}$ m/s should be assumed.

Based on this, a sufficiently reliable spatial distribution of permeability in the upper soil layers can be prepared, taking into account that upper layers dominated by gravel and sandy gravel soils exhibit good infiltration capacity ($k > 1 \times 10^{-4}$ m/s), whereas sandy soils and gravelly soils with more than 18% fine-grained fraction show poorer infiltration capacity ($k < 1 \times 10^{-5}$ m/s).

At the same time, recommendations can be developed on how the expected permeability class can be approximately assessed directly from the geotechnical description of a sample based on its silt content (Figure 4 – example for Ljubljana).

In Figure 4, the complete triangular diagram is shown on the left, while the right-hand side presents an enlarged view of the right part of the diagram. The enlargement shows in greater detail the permeability classes (−6, −5, −4) and more detailed silt contents (28%, 18%, and 12%), which represent the default thresholds between the respective classes.

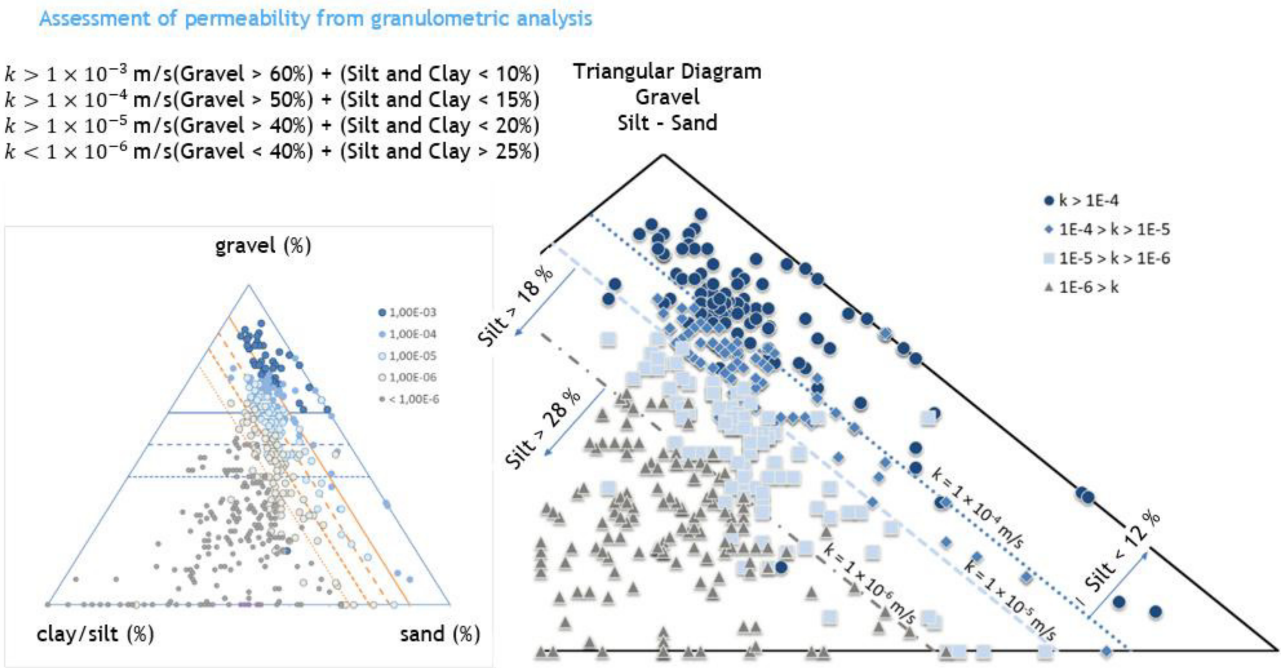



*Figure 4. Illustration of permeability assessment for sandy gravel material based on silt content – adapted for the Ljubljana example.*

The assessment of upper layer permeability must be conducted, regardless of the methods used, with knowledge and consideration of the geological, hydrogeological, and geotechnical conditions in the area under review. These conditions enable evaluation of the representativeness of archival data.

## 4.3. Limitations of infiltration capacity

| The key question for a geotechnical engineer is how much water can infiltrate and what the limitations are. |
| --- |

The basic definition of infiltration capacity is the permeability of the topsoil layers.

Top layers with permeability lower than $k = 5 \times 10^{-6}$ m/s (infiltration capacity of 15 mm/hour, 50 l/s/ha) allow effective drainage with greater retention, at least partial infiltration of stormwater on the building plot, and overflow. With such partial infiltration, even with overflow, a significant share of stormwater can still be returned to the aquifer, maintaining a large part of natural rainfall infiltration.

Soils are favourable for infiltration when permeability, measured as saturated hydraulic conductivity ($k_f$), ranges between $10^{-6}$ m/s and $10^{-2}$ m/s. Nevertheless, infiltration may still be recommended even if permeability is lower than $10^{-6}$ m/s, as appropriate measures can increase the soil's infiltration capacity or enable deeper percolation of water, for example by using an infiltration shaft or a buried trench.

Infiltration is generally not recommended on clay soils and wetlands, as these soils are already saturated to the surface and water movement is extremely limited and slow (Teller et al., 2023).

Further limitations to infiltration may arise from various conditions that can occur in a given area (TRCA, 2012; Hauts de Seine, 2011):

1. Shallow groundwater table

A seasonally high groundwater table less than 1 metre from the bottom of the infiltration system limits infiltration capacity for two reasons:

- the influence zone of infiltration increases, which at high water levels can extend to nearby structures, neighbouring land, or adjacent infiltration systems. In unfavourable cases, this may cause seepage.
- the retention role of the unsaturated zone is reduced, as high water can wash away retained pollutants.

A 1-metre thick unsaturated layer with permeability no greater than $k = 1 \times 10^{-3}$ m/s ensures basic natural filtration and sediment retention capacity. This prevents sediment transfer to the aquifer. Many pollutants bind to sediment particles, so filtration also limits pollutant transfer further into groundwater.

2. Perched Groundwater

Perched groundwater forms due to alternating layers of more permeable and less permeable layers. Consequently, the vertical permeability for rainfall infiltration is significantly reduced. This leads to at least occasional accumulation of groundwater on poorly permeable layers (see Chapter 5.2) before it drains into deeper layers.

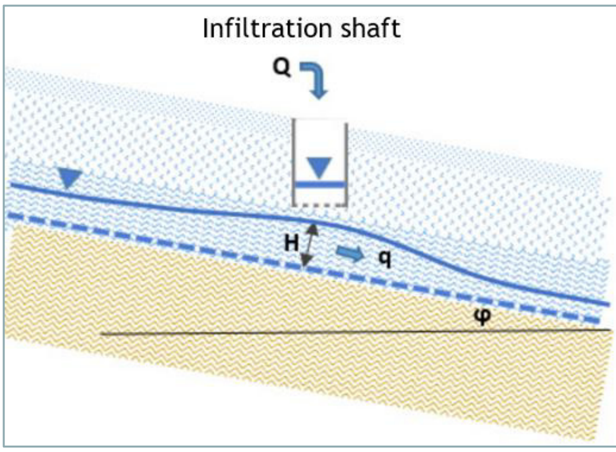
If perched groundwater is close to the surface, the influence zone of the infiltration system may expand, making standard recommended minimum setbacks insufficient. In such cases, a greater minimum distance from neighbouring structures, land, or infiltration systems must be considered. The minimum setback can be verified analytically or by using a model (see next point).

3. Proximity of neighbouring buildings or land parcels

The rise in groundwater level beneath an infiltration facility and the extent of the affected area are most significant where the unsaturated zone is thin, hydraulic conductivity is low, and rainfall intensities are high. The model is particularly sensitive to hydraulic conductivity and the thickness of the sediment layer. There are no simple analytical methods for calculating groundwater rise and the extent of its influence; therefore, simplified approaches and numerical models are used. Models such as HYDRUS allow for a more realistic representation of subsurface geometry and hydrogeological properties compared to classical analytical models (Carleton, G. B., 2010; Thompson et al., 2007; Ali, S., Islam, A., 2019). A reliable assessment can also be obtained using the online tool https://dss.inowas.com/tools/T02. Constraints due to impacts of $dh > 0.1$ m on neighbouring land parcels or structures are typically expected in cases of a thin aquifer layer (approximately 1 m), with low hydraulic conductivity ($k < 1 \times 10^{-5}$ m/s) and low effective porosity (10%).

4. Shallow Bedrock

During rainfall events, a temporary groundwater level forms on the bedrock surface; the retention capacity of suspended particles decreases; the groundwater level beneath the infiltration facility rises (Figure 5); the zone of influence of the infiltration facility expands; and previously retained pollutants are flushed from the unsaturated zone. The drainage capacity of sediments overlying shallow bedrock is already very limited at hydraulic conductivities of approximately $k \approx 1 \times 10^{-4}$ m/s.




$$H = \frac{Q}{k \cdot L \cdot i} = \frac{q}{k \cdot sin\varphi}$$

H = maximum rise of groundwater level beneath the infiltration shaft (m)
k = permeability of the saturated layer (m/s)
L = width of the infiltration shaft perpendicular to the flow direction (m)
Q = average daily inflow into the infiltration shaft ($m^3/s$)
q = inflow into the infiltration shaft per unit width of the shaft ($m^2/s$)
i = hydraulic gradient of the groundwater level (sin φ)

*Figure 5. Estimate of the maximum rise of the groundwater level beneath the infiltration system (adapted after Bernier, 2001).*

The presence of an aquifer less than 1 metre below the bottom of the infiltration system has a similar effect to a shallow groundwater table located less than 1 metre beneath the infiltration system.

In such cases, constructing infiltration systems is not feasible; instead, dispersed infiltration across the terrain, in shallow depressions or open trenches, should be considered. Infiltration using a layer of filter material is also possible.

5. Thick low-permeability cover layer

In practice, infiltration capacity is reduced if the thickness of poorly permeable cover layers in the upper part of the profile exceeds 3 metres. In this case, the infiltration depth is at least 2 metres less than usual, assuming the infiltration section typically begins below the frost zone.

Setting up an infiltration well or field requires larger excavation and more space.

An example is shown below (Figure 6): on the left, a 4 m deep infiltration well (PV-1) is located at a site without a confining layer and has a 3 m long infiltration section (at a depth of 1 to 3 m); on the right, a 3.5 m thick confining layer is present, and an infiltration well of the same depth (PV-2) can have an infiltration section only 0.5 m long (at a depth of 3.5 to 4 m).

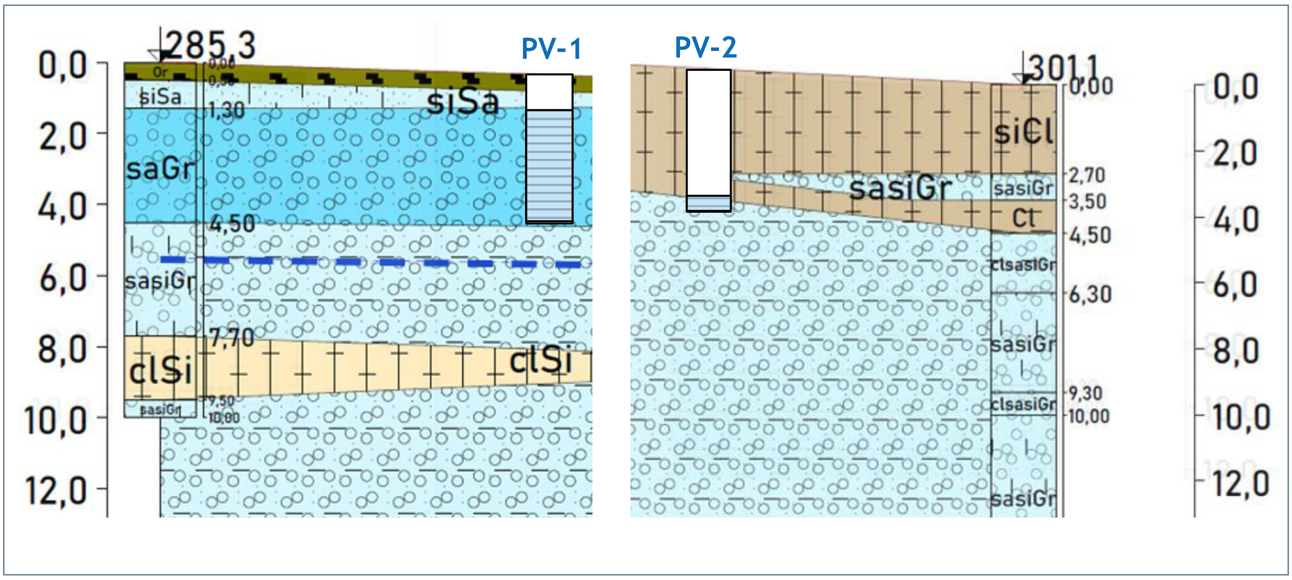



*Figure 6. Comparison of infiltration wells at a site without a confining layer (left) and with a 3.5 m thick confining layer (right).*

6. Sloping terrain

Areas with slopes greater than 20%, or contributing areas with gradients above 15%, may pose limitations for infiltration due to the risk of seepage onto lower-lying land, and in the worst cases, springs, internal erosion, or even instability and mass movements on unstable soils.

In such cases, greater setbacks from terrain breaks, terrace edges, or cliffs are required. At the same time, infiltration should be limited so that it does not exceed pre-development conditions. It is also recommended that infiltration be as distributed as possible to avoid localised rises in the groundwater level.

7. Flood-prone areas

Infiltration is generally considered unsuitable in flood-prone areas. These areas do not meet the basic requirement that the bottom of the infiltration system is at least 1 metre above the highest groundwater level. All retained pollutants are washed into the environment during high water events. Although transported in a highly diluted form, they subsequently settle and accumulate over a wider area in an uncontrolled manner.

8. Wetlands and associated saturated soils

Infiltration is not recommended on clay soils and wetlands, as these soils are already saturated to the surface and water movement is extremely limited and slow. In practice, excess water can only be removed through increased evapotranspiration.

9. Proximity to groundwater abstraction points

Drinking water wells can be significantly affected by infiltration systems due to microbiological contamination. Microorganisms can survive below the groundwater level for several to dozens of days. Minimum required distances vary greatly depending on conditions, particularly the speed of groundwater flow from the infiltration system towards the well. Even if the flow is not directed towards the well, a minimum distance of at least 30 metres should be maintained. However, each case must be analytically verified to ensure this distance is sufficient.

10. Contaminated areas, landfills, and polluted soils

Infiltration in areas with contaminated soil or subsoil would cause pollutants to be washed out and transported further into the environment.

Infiltration outside but near contaminated areas can alter the speed and direction of pollutant migration with groundwater flow, potentially redirecting contamination. Even seemingly minor changes in flow direction can have significant consequences for other abstraction points or remediation measures for degraded areas. If the infiltration system is located near existing wells used for monitoring groundwater quality within the affected area, the hydraulic anomaly caused by infiltrating a large volume of water can distort actual pollutant concentrations and affect the representativeness of sampling.

A greater setback is recommended – at least 250 metres from the boundary of the contaminated area or landfill.

11. Proximity to mining structures or other underground spaces

Voids beneath the ground surface represent empty spaces that can collapse or erode due to material washing. Infiltration that concentrates stormwater from a large sealed surface ($A_{imp}$) into a small infiltration area (Ap) has greater erosive power and can cause internal erosion if an empty space is nearby. The effect is similar to that of sloping terrain (see point 5).

Where such spaces may exist, infiltration volumes must be limited so they do not exceed natural infiltration, and the influence zone must not extend to these voids.

12. Presence of gypsum

The same applies as for swelling clays. When preparing an infiltration capacity map, it is necessary to check whether geological layers containing gypsum occur in the area. These layers should be shown separately, and it must be determined whether infiltration could increase contact between gypsum and water. Where such a risk exists, infiltration must be prohibited.

13. Presence of swelling clays

The same applies as for gypsum. When preparing an infiltration capacity map, it is necessary to check whether geological layers containing swelling clays occur in the area. These layers should be shown separately, and it must be determined whether infiltration could increase contact between swelling clays and water. Where such a risk exists, infiltration must be prohibited.

14. Protected areas

If infiltration is planned within a protected area, the specific restrictions and requirements for that area must be carefully reviewed.
In general, infiltration is acceptable if it does not result in:

- the presence of hazardous substances in groundwater,
- an increase in other substances or exceedance of the relative sensitivity of groundwater due to any substance,
- a change in groundwater temperature of more than 1°C on neighbouring land,
- a change in the direction of groundwater flow,
- a change in groundwater level of more than 0.1 m on neighbouring land.

These conditions may also apply when determining the setback distance for infiltration from a protected area, unless different conditions or distances are specified or agreed.

15. Frozen ground

A specific issue arises when rainfall infiltrates frozen ground without snow cover. This is a special case, similar to those listed in points 1–13. It is therefore recommended to design drainage elements that convey water to subsurface infiltration facilities, which are typically located below the frost zone and thus enable infiltration even when the ground surface is frozen.

# 5. Adaptation of the map to local climatic conditions

## 5.1. Rainfall intensity

The intensity of storm events can vary significantly between cities. The example below presents extreme rainfall values for Ljubljana (Table 1), which are relatively high. The values have been converted from $h_{(r,D)}$ (mm) to $q_{(r,D)}$ (l/s/ha) using data from the Crossrisk model. Data are typically presented in three formats: mm, mm/h, or l/s/ha. The conversions are given in Equations (5) to (7).

*Table 1. Example of return period data for extreme rainfall in Ljubljana [l/s/ha] (crossrisk.eu/sl/climate).*

| r (years)<br>D (min) | 1* | 2* | 5 | 10 | 25 | 50 | 100 | 250 |
|---|---|---|---|---|---|---|---|---|
| 5 | *320* | *358* | 400 | 467 | 567 | 633 | 667 | 767 |
| 10 | *217* | *246* | 283 | 333 | 400 | 450 | 500 | 583 |
| 15 | *175* | *199* | 233 | 267 | 322 | 367 | 411 | 478 |
| 20 | *145* | *166* | 192 | 233 | 275 | 317 | 358 | 417 |
| 30 | *117* | *133* | 156 | 183 | 222 | 250 | 283 | 333 |
| 45 | *90* | *103* | 122 | 141 | 174 | 196 | 222 | 263 |
| 60 | *75* | *86* | 100 | 119 | 144 | 164 | 186 | 219 |
| 90 | *58* | *66* | 78 | 93 | 111 | 128 | 144 | 170 |
| 120 | *48* | *55* | 64 | 76 | 92 | 106 | 119 | 140 |
| 180 | *37* | *43* | 50 | 58 | 70 | 81 | 91 | 106 |
| 240 | *31* | *35* | 41 | 49 | 58 | 66 | 74 | 88 |
| 300 | *27* | *31* | 36 | 42 | 50 | 57 | 64 | 74 |
| 360 | *24* | *27* | 32 | 37 | 44 | 50 | 56 | 65 |
| 540 | *19* | *21* | 24 | 28 | 33 | 37 | 42 | 48 |
| 720 | *15* | *17* | 20 | 23 | 27 | 30 | 34 | 38 |
| 900 | *13* | *15* | 17 | 19 | 23 | 25 | 28 | 32 |
| 1080 | *11* | *13* | 15 | 17 | 20 | 22 | 24 | 28 |
| 1440 | *9* | *10* | 12 | 13 | 16 | 17 | 19 | 22 |
| 2880 | *5* | *6* | 7 | 8 | 9 | 10 | 11 | 12 |
| 4320 | *4* | *4* | 5 | 6 | 6 | 7 | 8 | 9 |
| 5760 | *3* | *4* | 4 | 4 | 5 | 6 | 6 | 7 |
| 7200 | *3* | *3* | 3 | 4 | 4 | 5 | 5 | 6 |

**Interpolated values*

$1\ l/s/ha = 1\times10^{-7}\ m^3/s/m^2 = 1\times10^{-7}\ m/s$

$$q_{(r,D)}[l/s/ha] = \frac{h_{(r,D)}[mm]}{D[min]} \times 166{,}7 \qquad (3)$$

$$h_{(r,D)}[mm] = q_{(r,D)}[l/s/ha] \times D[min] \times 0{,}006 \qquad (4)$$

$$q_{(r,D)}[l/s/ha] = I_{(r,D)}[mm/h] \times 2{,}87 \qquad (5)$$

## 5.2. Infiltration capacity of soils in relation to characteristic rainfall events

### 5.2.1. Lower infiltration capacity

If the inflow of water from a storm event ($q_{(r,D)}$) exceeds the infiltration capacity of the land ($q_p$), water will accumulate on the surface and overflow from the site. The infiltration capacity of the soil is practically constant, while rainfall intensity varies. Therefore, excess inflow from the storm must be retained during the event when precipitation input exceeds the soil's infiltration capacity at the site ($q_{(r,D)} > q_p$).

$$V_p = q_p \times D \times A = h_p \times A \qquad (6)$$

$$h_p = q_p \times D \qquad (7)$$

$$V_{r,D} = h_{(r,D)} \times A \qquad (8)$$

$$q_p = \frac{k}{r_A} \times i \qquad (9)$$

| | |
|---|---|
| $q_{(r,D)}$ | Specific inflow from a storm event with a return period r (years) and duration *D* (minutes) [l/s/ha] |
| $I_{r,D}$ | Rainfall intensity (mm/h) |
| $q_p$ | Specific infiltration capacity [m³/s/m² = l/s/ha × 10⁻⁷] |
| $k$ | Permeability (m/s) |
| $i$ | Hydraulic gradient (-) |
| $D$ | Time (s) |
| $A$ | Land area (m²) |
| $h_p$ | Height of infiltrated (drained) water from the land (mm/m²) |
| $V_p$ | Volume of infiltrated (drained) water from the land (m³) |
| $A_{imp}$ | Impervious land area (m²) |
| $A_p$ | Infiltration area (m²) |
| $r_A$ | Ratio of impervious land area to infiltration area $A_{imp}$ / $A_p$ [-] |
| $h_{(r,D)}$ | Height of water from a storm event with a return period *r* (years) and duration *D* (minutes) (mm/m²) |
| $V_{r,D}$ | Volume of water from a storm event with a return period *r* (years) and duration *D* (minutes) (m³) |

In this case, the soil's permeability and infiltration capacity must be at least $k \geq 1.5 \times 10^{-6}$ m/s, or 15 l/s/ha, to ensure that a larger volume of water can infiltrate within one day than falls during a one-day, ten-year storm event (Figure 7). For runoff from one-day annual rainfall, the permeability must be at least $k \geq 1.0 \times 10^{-6}$ m/s and the infiltration capacity 10 l/s/ha.

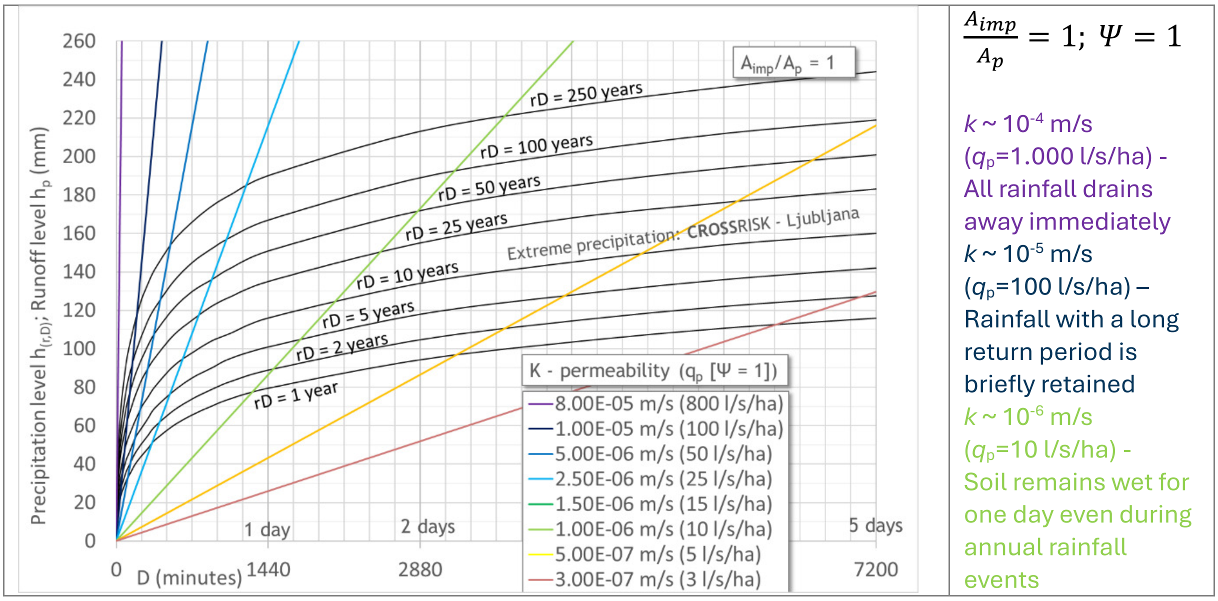



*Figure 7. Rainfall intensity (Ljubljana example) compared to soil infiltration capacity (D = 0 to 5 days).*

At a permeability of $k \approx 5 \times 10^{-7}$ m/s, or an infiltration capacity of 5 l/s/ha, the annual one-day rainfall exceeds the amount that can infiltrate into the subsoil. At a permeability of $k \approx 3 \times 10^{-7}$ m/s, or an infiltration capacity of 3 l/s/ha, the soil can still absorb water during annual four-day rainfall events (Figure 7).

### 5.2.2. Higher infiltration capacity

A permeability of $k \geq 1.75 \times 10^{-5}$ m/s, or an infiltration capacity of $q_p$ = 175 l/s/ha in the top layers, is already quite favourable, as during storms with a one-year return period there is no runoff from the plot if only 5 mm of rainfall (5 l/m² or 50 m³/ha) is temporarily retained on the land (Figure 8).

At a permeability of $k \approx 5 \times 10^{-5}$ m/s, or an infiltration capacity of $q_p$ = 500 l/s/ha, storms with a return period of up to 10 years do not even temporarily remain in the soil.

At a permeability of $k > 8 \times 10^{-5}$ m/s, even storms with a return period of 250 years infiltrate immediately (Figure 8).

Under natural conditions, we assume that the entire land surface participates in infiltration. If we want the rainfall water on the land to infiltrate only through part of the land ($A_p$), its infiltration capacity is proportionally reduced according to how much smaller the infiltration area is compared to the drained sealed area ($A_{imp}$ / $A_p$).

$$q_p = \frac{k}{r_A} \times i \qquad (10) \qquad\qquad r_A = \frac{A_{imp}}{A_p} \qquad (11)$$

$i = 1 \wedge r_A = 1 \Rightarrow q_p = k$ (1 l/s/ha = $1 \times 10^{-7}$ m$^3$/s/m$^2$ = $1 \times 10^{-7}$ m/s)

Example: $i$ = 1; $r_A$ = 1; $k = 1{,}75 \times 10^{-5}$ m/s ⇒ $q_p$ = 175 l/s/ha; $r_A$ = 10 ⇒ $q_p$ = 17,5 l/s/ha

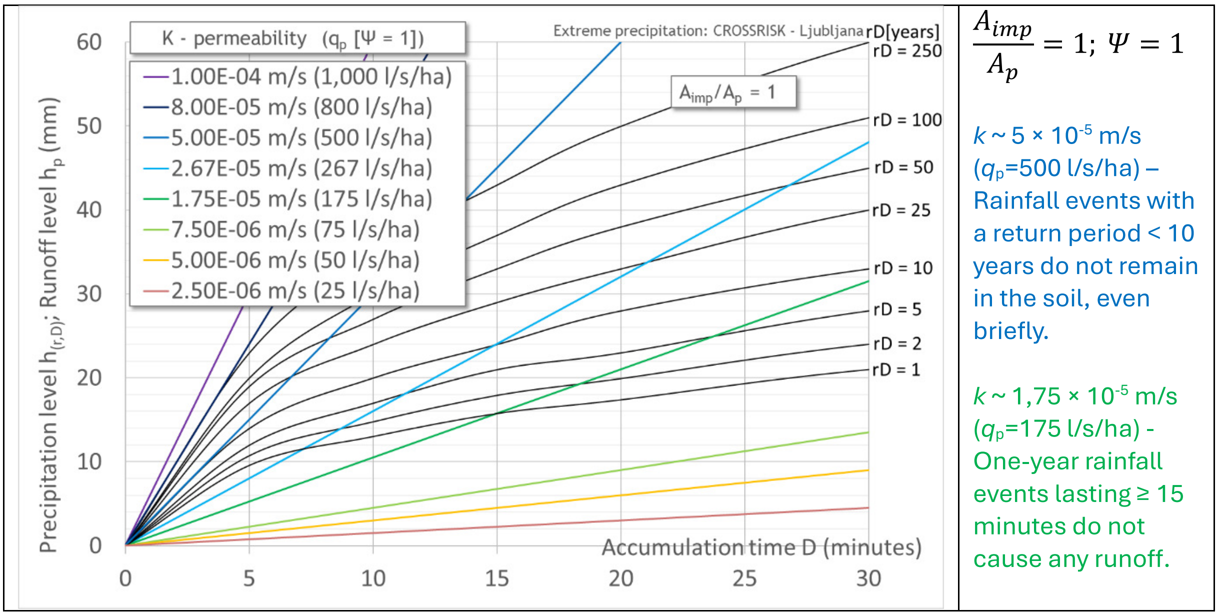



*Figure 8. Rainfall intensity (example: Ljubljana) compared to soil infiltration capacity (D = 0 to 30 minutes).*

### 5.2.3. Natural runoff

The natural retention capacity of rainfall on land can partially hold precipitation, preventing it from running off at full intensity. Similar to the rainfall threshold, we can assume that a small retained volume or depth - probably around 5 to 10 mm - is held within the first 15 minutes. If at least 5 mm can be retained on the land and if 175 l/s/ha ($q_{(1,15)}$) can drain away, then this runoff amount will not be exceeded, even though the 5-minute intensity is almost twice as high, i.e., 320 l/s/ha ($q_{(1,5)}$) (Figure 8, Table 1).

Natural conditions in areas of urban development usually consist of land with grass or overgrown surfaces, gardens, arable soil, with flat to steep slopes. The runoff coefficient in such an initial state, $\Psi_0$, ranges between 0.0 and 0.3. In general, we can calculate that the surface runoff to be managed from these lands in their initial state, $q_0$, is approximately 10%-20% of the rainfall water $q_{(r,D)}$:

$$q_{(r,15)}\ (\mathrm{l/s/ha}) \times \Psi_0 = 0{,}1 \times q_{(r,15)} < q_0 < q_{(r,15)}\ (l/s/ha) \times \Psi_0 = 0{,}2 \times q_{(r,15)} \qquad (12)$$

If we manage land for safety with a return period of 5 years and design the drainage system accordingly, in the example shown we need to account for a system capacity of 23.3 to 46.6 l/s/ha (Table 2). If the land consists mainly of areas with gentle slopes, the drainage system would be designed for a runoff of 23.3 l/s/ha.

*Table 2. Fifteen-minute storms with return periods of 1–10 years (Figure 9).*

| | $h_{(r,15)}$ (mm) | $q_{(r,15)}$ (l/s/ha) | $q_{(r,15)}$ (l/s/ha); $\Psi_0$=0.1 | $q_{(r,15)}$ (l/s/ha); $\Psi_0$=0.2 |
|---|---|---|---|---|
| *r*=1 year | 16 | 175 | 17.5 | 35 |
| *r*=2 years | 18 | 199 | 19.9 | 39.8 |
| *r*=5 years | 21 | 233 | 23.3 | 46.6 |
| *r*=10 years | 24 | 267 | 26.7 | 53.4 |

## 5.2.4. Increased runoff after interventions

Interventions and construction on land can significantly increase impermeable surfaces and the overall runoff coefficient $\Psi_m$. This substantially increases rainwater runoff during storms. The expected range for the runoff coefficient $\Psi_m$ of a building plot is approximately 0.2 to 0.8 (Figure 9).

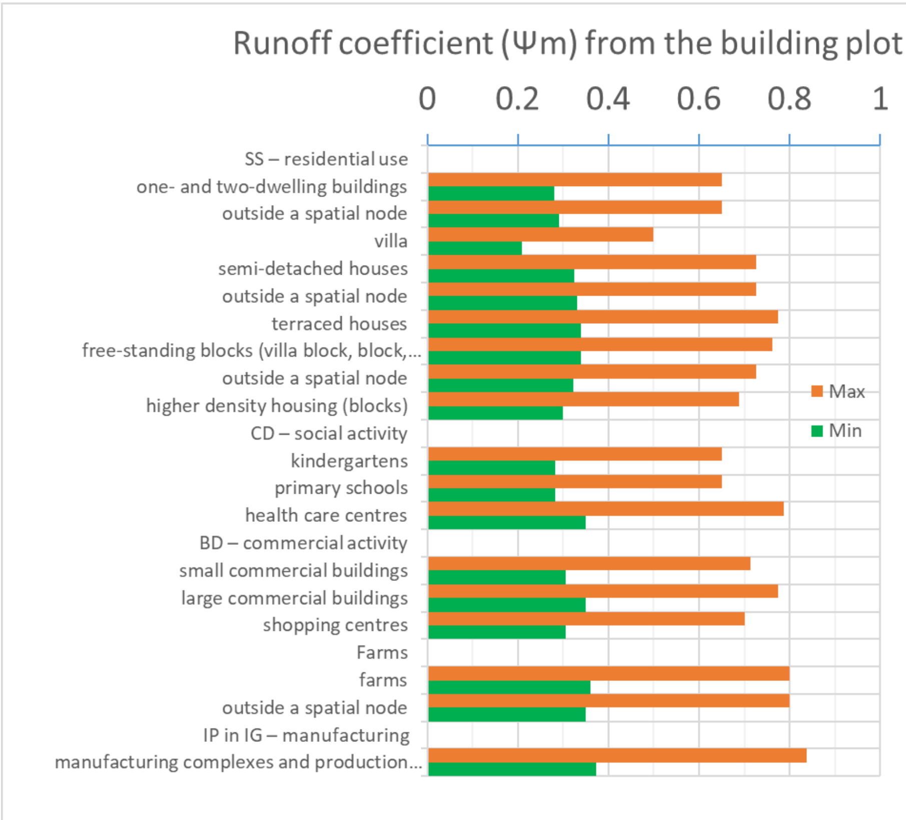



*Figure 9. Calculated range of runoff coefficients for various building plots.*

For example, consider a typical building plot of 310 m² intended for a terraced house. The maximum runoff during a storm with a two-year return period is estimated to increase from 0.62 l/s to 3.98 l/s (Table 3). In this case, the runoff increased due to the rise in impermeable surfaces and the overall runoff coefficient from $\Psi_m$ = 0.1 to $\Psi_m$ = 0.65.

To ensure that the runoff after the intervention does not exceed 0.62 l/s, stormwater must be temporarily retained and discharged slowly or in a throttled manner. Otherwise, the increased runoff will burden neighbouring land, drainage ditches, or the sewer system.

If all excess water resulting from the intervention and increased impermeability can infiltrate, retention or discharge into surface ditches, water bodies, or the sewer system is unnecessary.

*Table 3. Example of runoff change for a building plot with a terraced house.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Terraced house** | 310 | m² | q[n(years), T(minutes)] l/s/Ha | q[2,15] | 199 |
| | | | **New situation** | | | | New situation |
| | | **Surfaces** | **m2** | **Ψm** | | **A imp (m²)** | outflow l/s |
| BF | 48% | Built-up area | 150 | 0.9 | Sloped roof – roof tiles | 135 | 2.69 |
| USI | 23% | Unsealed surface | 70 | 0.1 | Meadow, flat surface | 7 | 0.14 |
| FP-L | 6% | Paved external surfaces intended for living - green | 20 | 0.15 | Paving stones with grass in betv | 3 | 0.06 |
| | 6% | Paved external surfaces intended for living - paved | 20 | 0.5 | Solid paving with gravel | 10 | 0.20 |
| FP-T | 16% | Paved external areas for transport, utilities and technical purposes | 50 | 0.9 | Asphalt, seamless concrete | 45 | 0.90 |
| | | **TOTAL** | **310** | **0.65** | | **200** | 3.98 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | 310 | | q[n(lyears), T(minutes)] l/s/Ha | q[2,15] | 199 |
| | | | **Baseline situation** | | | | Baseline situation |
| | | **Surfaces** | m² | Ψm | | A imp (m²) | outflow l/s |
| | | Built-up area | 0 | 0.9 | Sloped roof – roof tiles | 0 | 0.00 |
| | 100% | Unsealed surface | 310 | 0.1 | Meadow, flat surface | 31 | 0.62 |
| | | Paved external surfaces intended for living - green | 0 | 0.15 | Paving stones with grass in betv | 0 | 0.00 |
| | | Paved external surfaces intended for living - paved | 0 | 0.6 | Solid paving with gravel | 0 | 0.00 |
| | | Paved external areas for transport, utilities and technical purposes | 0 | 0.9 | Asphalt, seamless concrete | 0 | 0.00 |
| | | **TOTAL** | **310** | **0.10** | | **31** | 0.62 |
| | | | | | | **Difference (l/s):** | 3.36 |

## 5.2.5. Retention of increased runoff

The need to retain excess runoff caused by land interventions (construction, landscaping, etc.) depends on site stability, soil infiltration capacity, drainage ditch or watercourse capacity, and ultimately, sewer system capacity. It may also depend on a combination of these factors.

The infiltration capacity $q_p$ (m/s) primarily depends on permeability $k$ (m/s) and the infiltration area $A_p$ (m²). If stormwater is to be infiltrated on an area representing one-tenth of the sealed surface ($r_A$ = 10), the infiltration capacity will be ten times smaller:

$$q_p(\mathrm{m/s}) = \frac{k\left(\frac{\mathrm{m}}{\mathrm{s}}\right) \times i}{r_A} \qquad (13)$$

During a storm, when inflow exceeds infiltration capacity, retention must be provided.

The specific volume $V'_z$ (m³/m²), or retention depth $\Delta h$ (mm), depends on the ratio $r_A$ between the sealed surface $A_{imp}$ (m²) and the infiltration area $A_p$ (m²), the permeability coefficient $k$ (m/s), and the storm return period $r$ (years) (see Figure 10, Figure 11).

Equation for $V'_z$ and Δh: $V'_z = \Delta h = D\left(q_{(r,D)} - q_p\right)$ (14)

Based on this, typical curves can be developed for a given location to calculate the specific retention volume (see Figure 12, Table 4).

The required maximum retention volume $V_z$ is then calculated as:

$V_z = \Delta h \cdot A_{imp}$ (15)

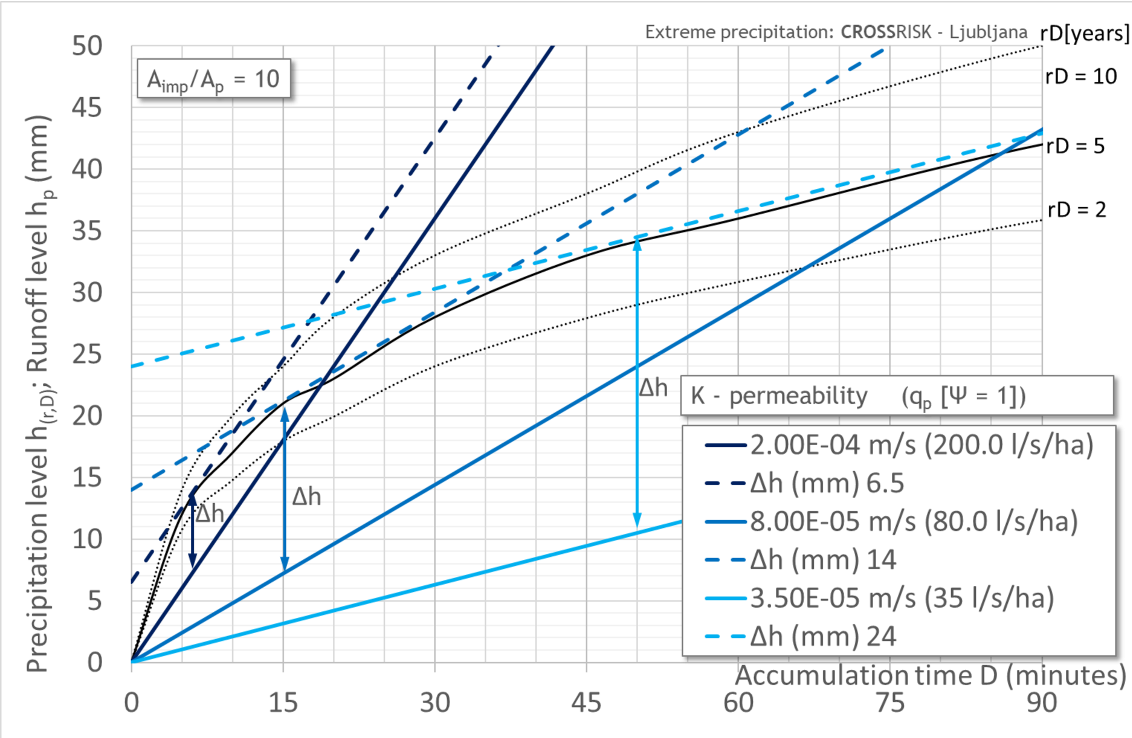



*Figure 10. Retention depth Δh (mm) as a function of k (m/s), $r_A$ = 10, r = 2, 5, 10 (years); example: Ljubljana.*

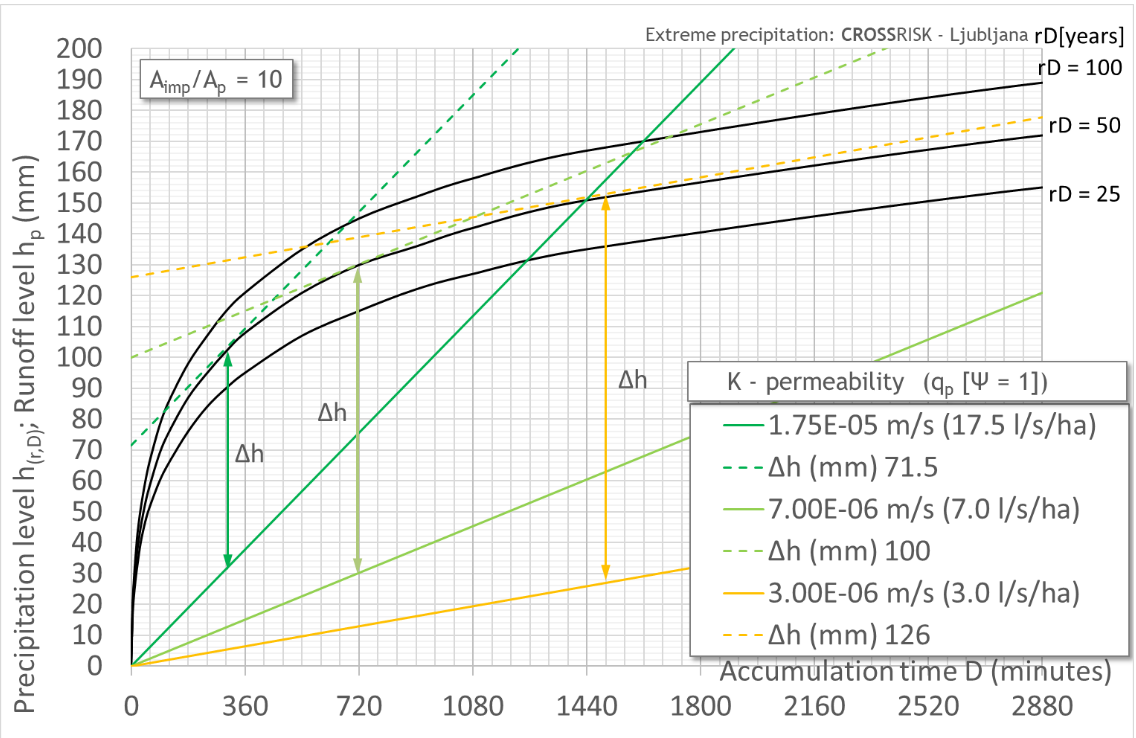



*Figure 11. Retention depth Δh (mm) as a function of k (m/s), $r_A$ = 10, r = 25, 50, 100 (years); example: Ljubljana.*

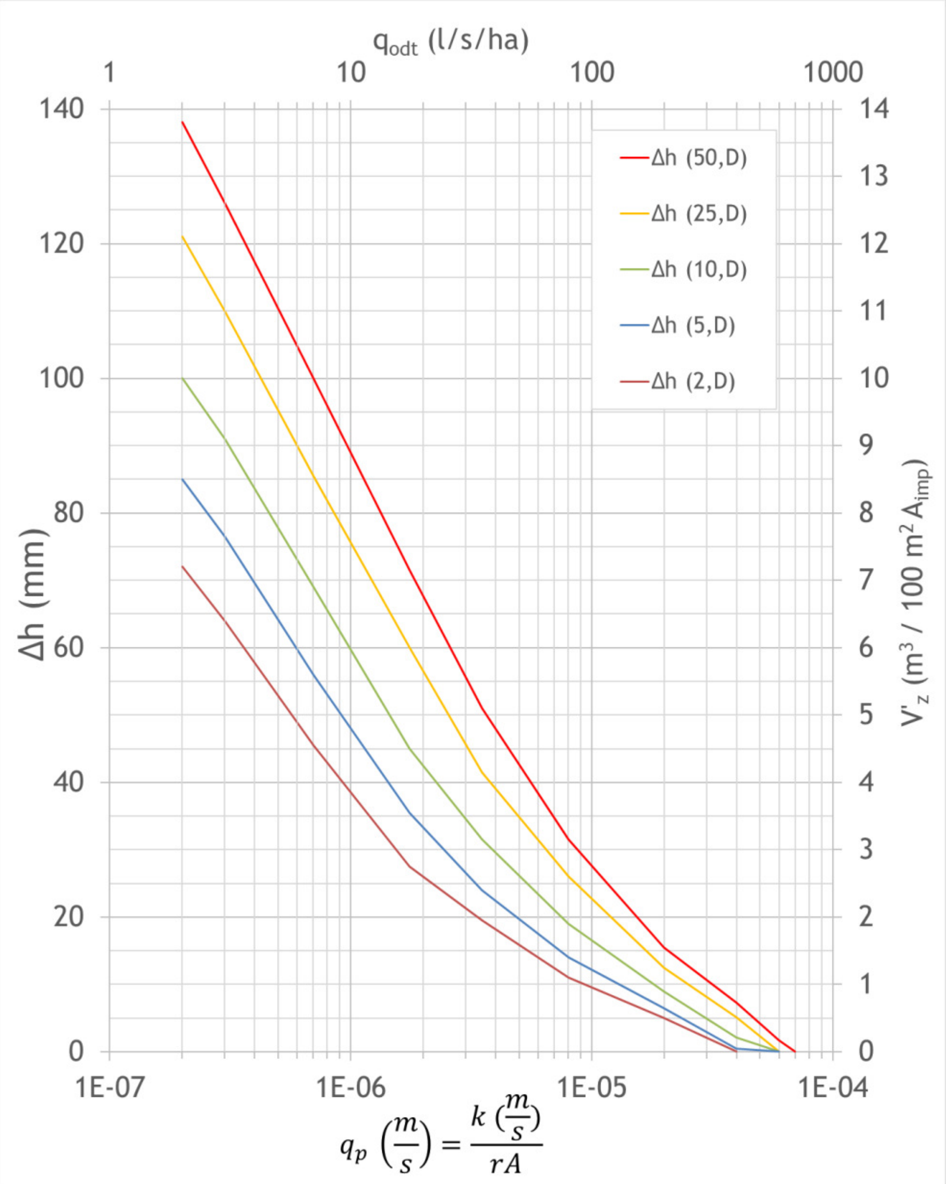



*Figure 12. Typical curves for Ljubljana for calculating specific retention volume for stormwater.*

*Table 4. Retention depths Δh (mm) for storms with different return periods and durations (r, D).*

| *k* (m/s) | *Δh* (2,D) | *Δh* (5,D) | *Δh* (10,D) | *Δh* (25,D) | *Δh* (50,D) |
|---|---|---|---|---|---|
| **2,00E-07** | 72 | 85 | 100 | 121 | 138 |
| **3,00E-07** | 64 | 76,5 | 91 | 110 | 126 |
| **7,00E-07** | 45,5 | 56 | 69 | 85,5 | 100 |
| **1,75E-06** | 27,5 | 35,5 | 45 | 60 | 71,5 |
| **3,50E-06** | 19,5 | 24 | 31,5 | 41,5 | 51 |
| **8,00E-06** | 11 | 14 | 19 | 26 | 31,5 |
| **2,00E-05** | 5 | 6,5 | 9 | 12,5 | 15,5 |
| **4,00E-05** | 0 | 0,5 | 2,1 | 5,1 | 7,3 |
| **6,00E-05** | | 0 | 0 | 0 | 1,7 |
| **7,00E-05** | | | | | 0 |

To estimate the required retention volume for storms with different return periods, it is necessary to know the soil permeability coefficient ($k$) and the planned ratio between sealed and infiltration surfaces ($r_A$).

Using this information, the infiltration capacity $q_p$ is calculated, and the specific retention volumes $V'_z$ ($m^3/m^2$) for storms with various return periods are then obtained from the typical curve. By multiplying the specific retention volume by the sealed surface $A_{imp}$, the required retention volume $V_z$ ($m^3$) for a storm with the selected return period $r$ (years) is determined (Figure 12).

If, in addition to infiltration, another discharge method is planned (such as to the surface, ditch, watercourse, or sewer), the permitted discharge value is added to the infiltration capacity, and the curve is then used to determine the specific retention volume.

The terraced house example (Table 3) can be used to illustrate the threshold values of permeability or infiltration capacity on the Infiltration capacity map.

*Example of a terraced house (Table 3):*

In this example, it is assumed that the infiltration area will cover at least 20% of the sealed surface ($r_A$ = 5). The total vegetated area (USI ≥ 0.2) is 70 m², and the sealed surface $A_{imp}$ = 200 m². The infiltration area would therefore occupy $A_p$ = 40 m², which is more than half of the total vegetated terrain. Such a ratio between sealed and vegetated surfaces is very favourable for stormwater treatment, especially if infiltration is carried out through green areas, i.e., biologically active soil.

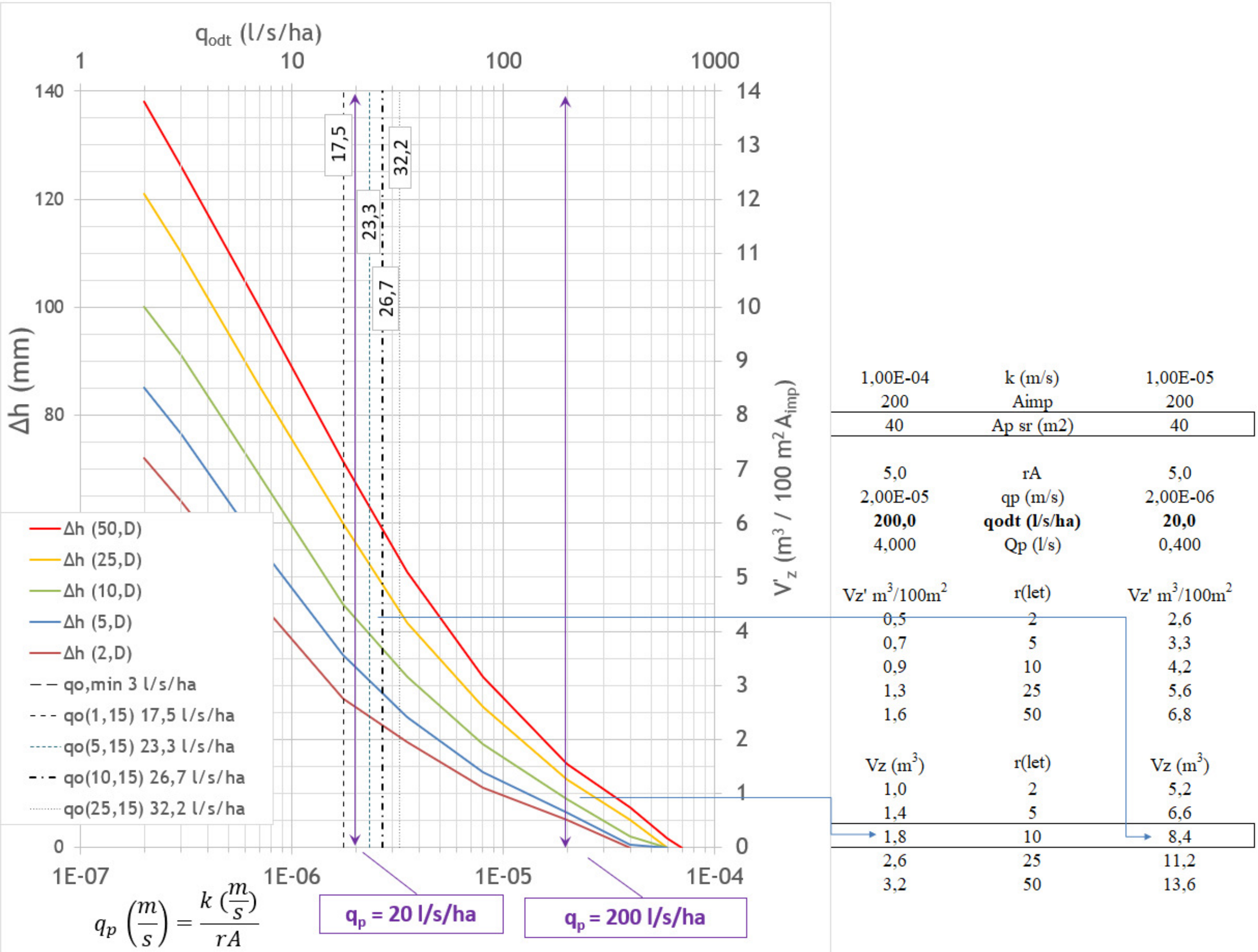



*Figure 13. Example of calculating retention volumes for storms with different return periods using typical curves for Ljubljana.*

1) Permeability ≥ 1 × 10⁻⁵ m/s (moderate infiltration capacity):

For moderate infiltration capacity, the maximum required retention volume is up to 5.2 m³ (2-year return period) or 8.4 m³ (10-year return period) (Figure 13). If a depression is created on a 40 m² infiltration area on vegetated terrain, during a 10-year storm it would hold water to a depth of 21 cm, which would drain away in 5.8 hours (Table 5).

2) Permeability ≥ 1 × $10^{-4}$ m/s (good infiltration capacity):

For good infiltration capacity, the maximum required retention volume is 1.0 $m^3$ (2-year return period) or 3.2 $m^3$ (50-year return period) (Figure 13). If a depression is created on a 40 $m^2$ infiltration area on vegetated terrain, during a 50-year storm it would hold water to a depth of 8 cm, which would drain away in 2.2 hours (Table 5).

*Table 5. Water depth in the depression dH (m) and emptying time t (h) for good and moderate infiltration capacity.*

| | 1 × $10^{-4}$ m/s | | 1 × $10^{-5}$ m/s | |
|---|---|---|---|---|
| Return period | Water depth | Emptying time | Water depth | Emptying time |
| *r* (years) | *Δh* (m) | $q_p$(h) | *Δh* (m) | $q_p$ (h) |
| 2 | 0.025 | 0.7 | 0.13 | 3.6 |
| 5 | 0.035 | 1.0 | 0.165 | 4.6 |
| 10 | 0.045 | 1.3 | 0.21 | 5.8 |
| 25 | 0.065 | 1.8 | 0.28 | 7.8 |
| 50 | 0.08 | 2.2 | 0.34 | 9.4 |

# 6. Map graphics of infiltration capacity

## 6.1. Representation of infiltration capacity

Priority activities in managing stormwater runoff depend on the specific local community or country and may prioritise either infiltration or retention of stormwater from heavy rainfall events.

In best practice examples (Chapter 1.2), areas on “infiltration potential” or infiltration capacity maps are classified into categories that define the suitability of an area for stormwater infiltration, such as high potential, moderate potential, low potential, and restricted areas where infiltration is not recommended or is prohibited.

In the example shown for Ljubljana, based on local hydrogeological conditions (Chapter 4) and climatic conditions (Chapter 4.3), it is appropriate to present the infiltration capacities of the top layers within its functional urban area in three classes (Figure 16):

1- High infiltration capacity: $q_p > 1 \times 10^{-4}$ m/s

2- Moderate infiltration capacity: $1 \times 10^{-4}$ m/s $> q_p > 1 \times 10^{-5}$ m/s

3- Low infiltration capacity: $q_p < 1 \times 10^{-5}$ m/s

The infiltration capacity map presents three main categories and guidelines for infiltration:

1: High infiltration capacity:

Full infiltration of stormwater from heavy rainfall is feasible, with little or no need for retention.

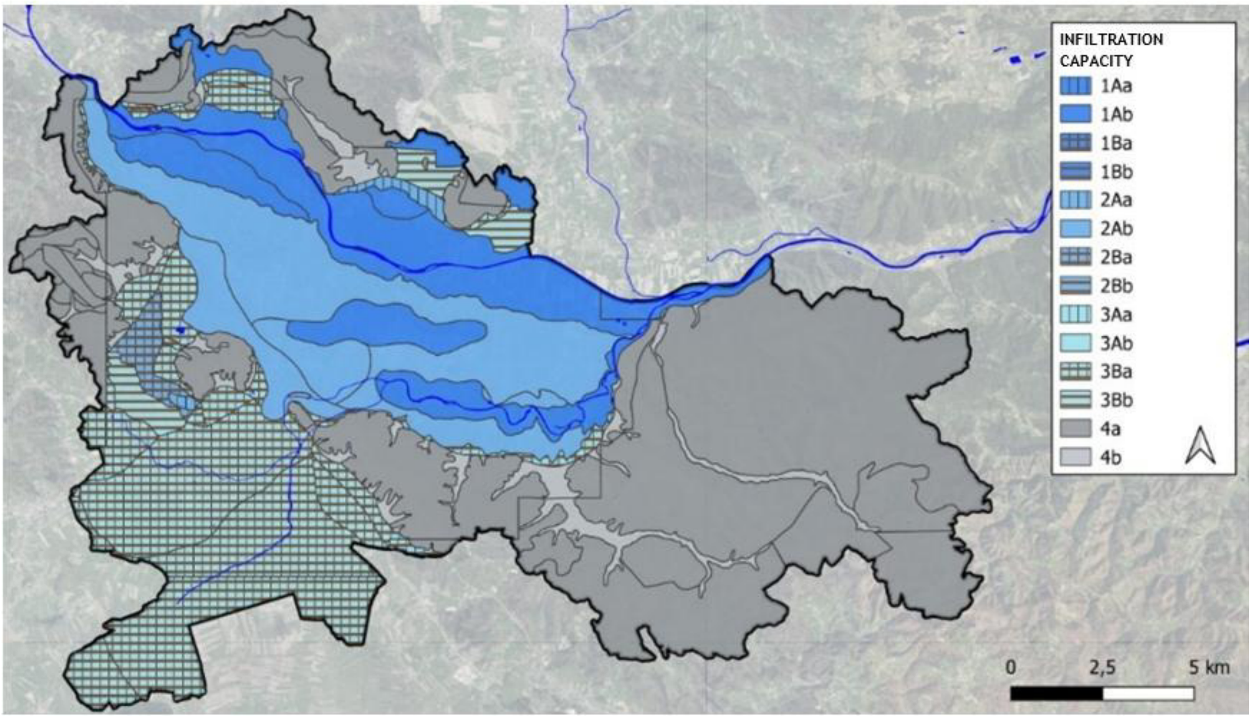
2: Moderate infiltration capacity

Full infiltration of stormwater from heavy rainfall is feasible with retention, or infiltration of a larger portion of stormwater with at least partial permitted discharge.

3: Low infiltration capacity

Infiltration is feasible only for very small amounts of stormwater from heavy rainfall, with retention and permitted discharge. The infiltration volume is too small to significantly reduce the required retention volume. Its main importance is in restoring natural infiltration, replenishing aquifers and springs, and maintaining pore water pressure in foundation soils to prevent settlement and soil desiccation.

Permitted discharge into a watercourse or, ultimately, into the sewer system should allow a volume at least equivalent to the natural surface runoff of the land. Natural runoff can be defined as runoff from relatively flat grassy land, i.e., with a runoff coefficient $\Psi_m$ = 0.1 or within the range of 0.05 to 0.15.




| Hydraulic conductivity | Infiltration capacity | Infiltration capacity |
|---|---|---|
| 1: good (k > $1\times10^{-4}$ m/s) | 1: good ($q_p$ > 6 mm/min) | 1: good ($q_p$ > 1000 l/s/ha) |
| 2: medium ($1\times10^{-5}$ < k (m/s) < $1\times10^{-4}$) | 2: medium (0,6 < $q_p$ (mm/min) < 6) | 2: medium (100 < $q_p$ (l/s/ha) < 1000) |
| 3: poor (< $1\times10^{-5}$ m/s) | 3: poor (<0,6 mm/min) | 3: poor (<100 l/s/ha) |
| Groundwater directly above the bedrock | | |
| Groundwater in valley | | |

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

*Figure 14. Graphical representation of the Infiltration capacity map for Ljubljana, showing layers based on hydraulic conductivity, confining layer thickness, and depth to groundwater.*

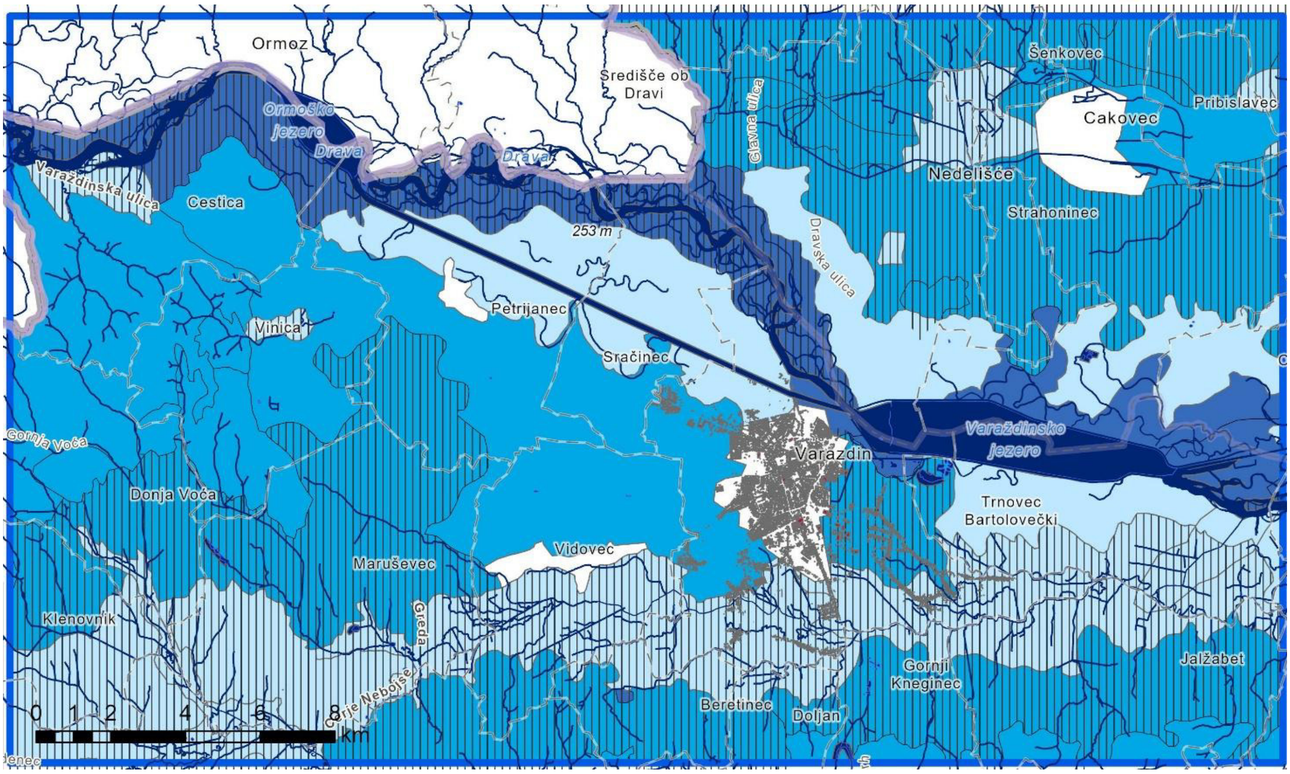
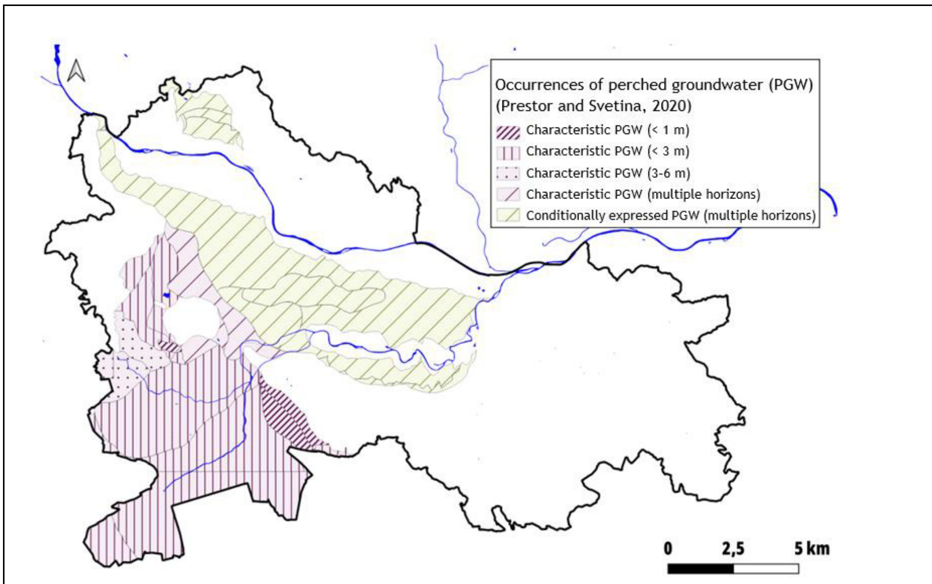



*Figure 15. Graphical representation of the Infiltration capacity map for Varaždin, showing layers based on hydraulic conductivity, confining layer thickness, and depth to groundwater.*

| *Infiltration capacity (m/s)* | |
|---|---|
| | *Good (k>1x10⁻⁴ m/s)* |
| | *Medium (1x10⁻⁵ < k (m/s) < 1x10⁻⁴)* |
| | *Poor (k < 1x10⁻⁵ m/s)* |
| | *Settlements;* |

| *Thickness of overlaying strata (m)* | |
|---|---|
| | *< 2 m* |
| | *> 2 m* |




Characteristics of perched groundwater occurrences:

1 – typical perched groundwater occurrence
2 – conditionally expressed perched groundwater

Depth of perched groundwater occurrences:
a- depth of occurrence <1m
b- depth of occurrence <3m
c- depth of occurrence 3-6m
d- depth of occurrence 6-9m
e- depth of occurrence 9-12m
f- various horizons of occurrence

*Figure 16. Graphic representation of the Infiltration Capacity Map for the Ljubljana example.*

The same applies to areas where infiltration is significantly restricted due to:

- shallow high groundwater levels, resulting in insufficient pollutant retention capacity, seepage into neighbouring structures, or reduced infiltration potential on adjacent land;
- shallow bedrock, which may affect neighbouring land through seepage or internal erosion;
- perched groundwater tables, which may cause excessive seepage or reduce infiltration capacity on adjacent land.

## 6.2. Characteristic cross-sections

The infiltration capacity map should include as many characteristic hydrogeological cross-sections as possible, illustrating all typical top layers according to their infiltration capacity.

The cross-sections should indicate the permeability category, groundwater level, perched groundwater tables, and the thickness of cover layers (Figure 17, Figure 18, Figure 19).

## 6.3. Conditions of use

The conditions of use must be clearly stated in the standard metadata description. In particular, the purpose of the layers, attributes, owner, author, maintainer, distributor, accessibility, limitations, and exclusions must be explicitly defined and described.

## 6.4. Map maintenance and updating

Provision must be made for the maintenance and updating of the map. The maintenance and update protocol must be developed by the GIS department in coordination with stakeholders. For updating, a time interval should be defined to ensure that new data can be processed and verified, and that the map does not become outdated during this period.

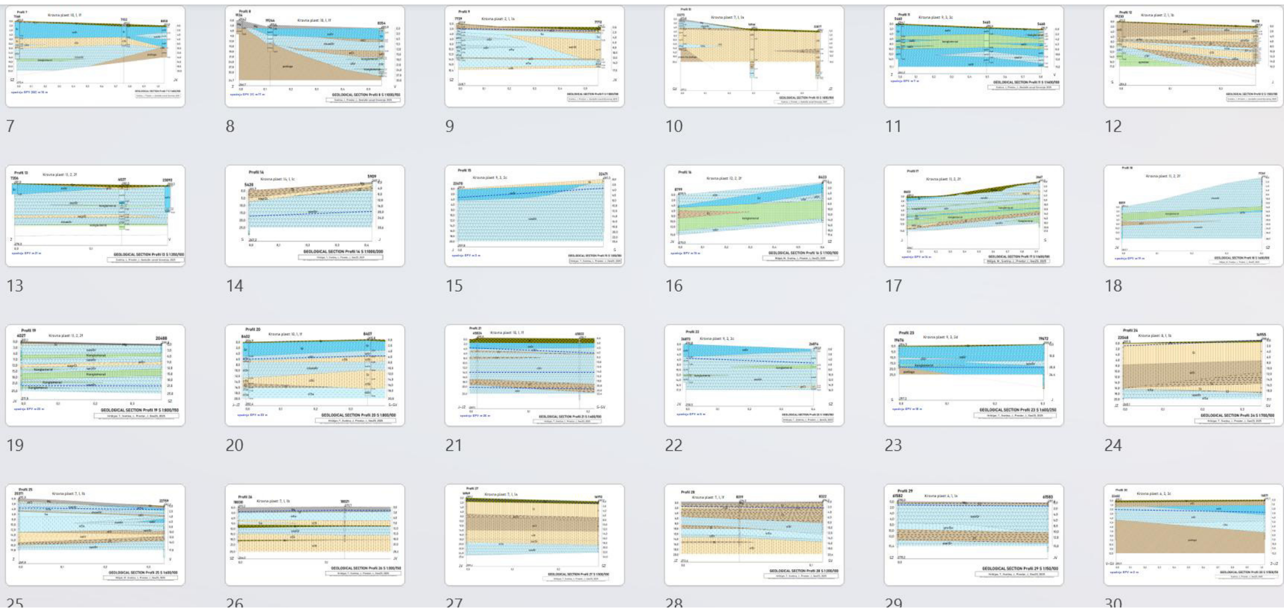



*Figure 17. Excerpt from an example set of hydrogeological cross-sections with data on subsurface infiltration capacity.*

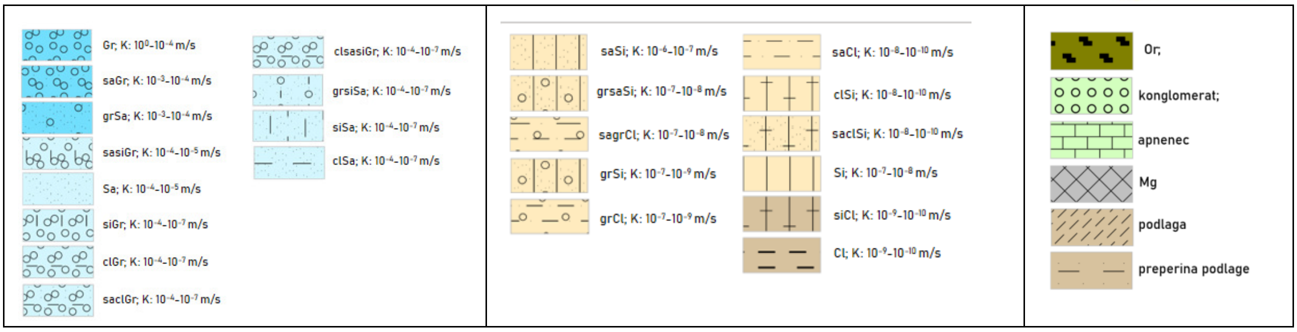



*Figure 18. Example from the legend of hydrogeological cross-sections with data on subsurface infiltration capacity.*

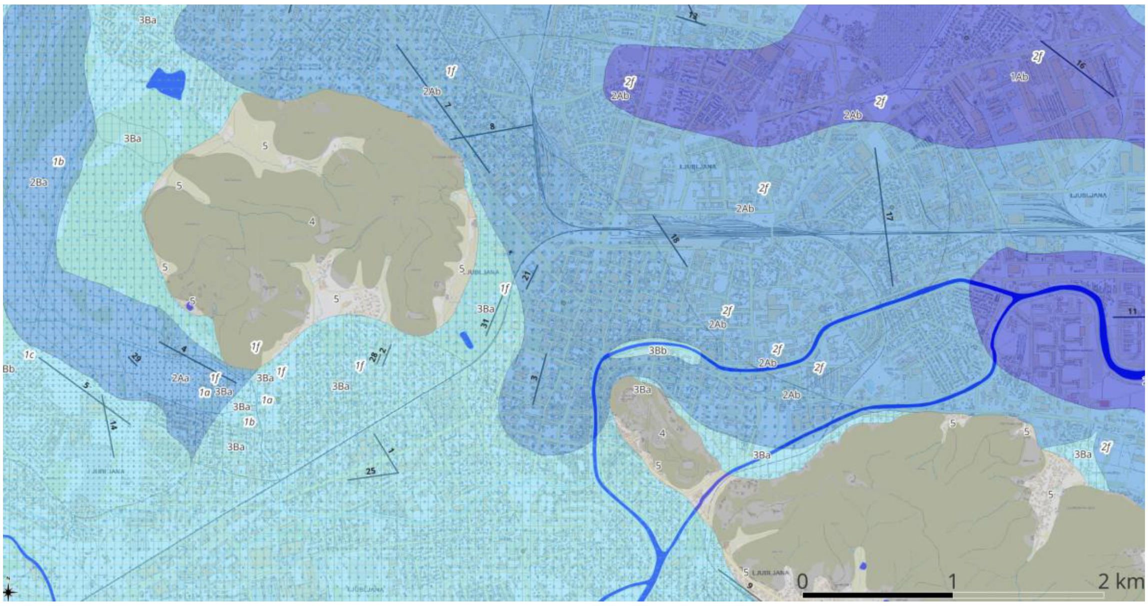



*Figure 19. Example excerpt from the infiltration capacity map showing the locations of characteristic hydrogeological cross-sections.*

# C. PRACTICAL USE OF THE INFILTRATION CAPACITY MAP

## 7. Basis for the "Urban stormwater drainage concept"

### 7.1. General guidelines

| | |
|---|---|
| *Excess Stormwater* | Excess stormwater arises from interventions or land modifications that increase the site's runoff coefficient. |
| *Responsibility for stormwater drainage* | Rainfall on a property should naturally infiltrate or drain into the natural environment within that property.<br>If a stormwater sewer system is unavailable or has insufficient capacity, the property owner is solely responsible for arranging stormwater drainage and retention. The owner must implement drainage and necessary facilities appropriate to the land and its use.<br>The owner must ensure proper drainage and, if necessary, treatment of stormwater. |
| *Preferred solutions* | Solutions for managing excess stormwater should prioritise infiltration on the property.<br>The drainage system includes three discharge methods:<br>1. infiltration,<br>2. discharge into surface waters, and<br>3. discharge into the stormwater sewer system.<br>Drainage must be planned in this strict order of priority.<br>If infiltration alone is not feasible, combinations or the other two methods should be considered. |
| *Runoff from the property* | Stormwater drainage must be designed so that the maximum runoff from the property is less than or equal to the runoff before the intervention. |
| *Prohibitions* | Discharge of municipal or industrial wastewater into the stormwater sewer system is prohibited. |

## 7.2. Detailed guidelines based on land infiltration capacity

*Drainage design – case 1:*

- Lower infiltration capacity

In areas with lower infiltration capacity, drainage systems are designed to allow partial infiltration of stormwater, with a permitted discharge to the surface water or stormwater sewer system and overflow.

It is recommended that overflows be permitted for rainfall events with return periods, for example, 5 years (also based on the damage potential at the specific site).

It is recommended that the permitted discharge (throttled outflow) be provided in one of the following ways (see Figure 20):

- at a rate corresponding to the capacity of the stormwater sewer system;
- at a rate corresponding to natural runoff, $\Psi_m$ = 0.1, with a return period $r$ = 1;
- at a rate corresponding to natural runoff $q_{thr} = q_{0(r,15)}$ = … l/s/ha (e.g. $q_{0(1,15)}$ = 17.5 l/s/ha);
- at a rate corresponding to the minimum recommended value (e.g. $q_{thr}$ = 3 l/s/ha for uninhabited or sparsely populated areas, or $q_{thr}$ = 10 l/s/ha for more densely populated areas);
- at a rate corresponding to the minimum value required for reservoir emptying or for exceptionally permitted discharges in combined sewer areas or in areas sensitive in terms of ecosystem protection and geotechnical stability, e.g. $q_{thr}$ = 2 l/s/ha.

- Shallow groundwater table or shallow bedrock

In areas with shallow bedrock and a groundwater table less than 3 m below the surface, drainage systems without infiltration or with partial distributed infiltration are implemented, together with a defined permitted discharge and a defined permitted overflow to the sewer system.

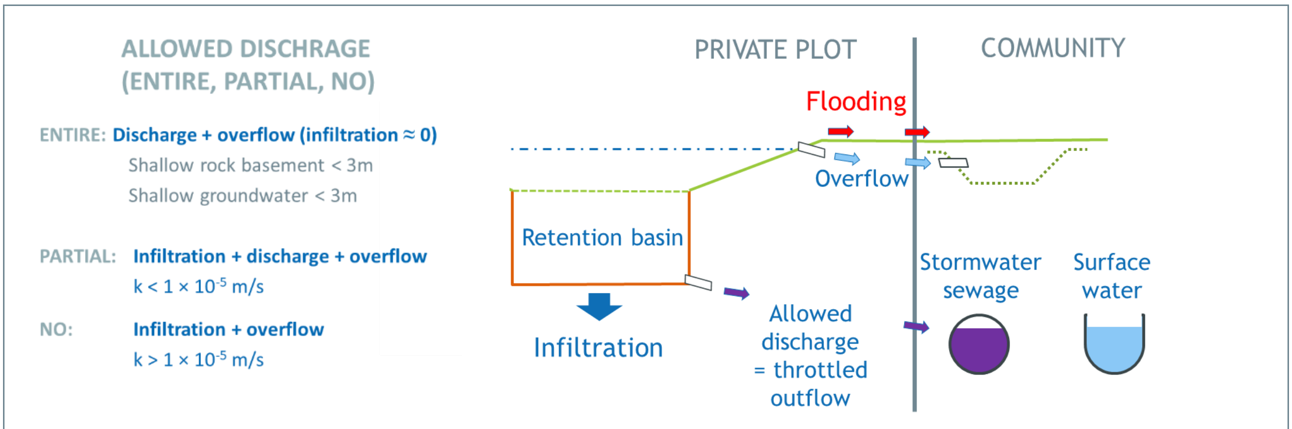



*Figure 20. The role of permitted discharge in stormwater drainage.*

- Moderate infiltration capacity

In areas with moderate infiltration capacity, drainage systems are designed to allow infiltration of the entire volume of stormwater, with provision for overflow to drainage channels and flood or spreading areas.

It is recommended that overflows be provided for rainfall events with a return period exceeding, for example, 10 years.

- Good infiltration capacity

In areas with good infiltration capacity, drainage systems are designed to allow infiltration of the entire volume of stormwater.

It is recommended that infiltration-based drainage be ensured for all rainfall events with a return period of, for example, 30 years.

*Drainage design – case 2:*

**A. Infiltration**

Infiltration must be adapted to all potential limitations of infiltration capacity (see Chapter 4.3), and above all aligned with stability risks, seepage on the property and neighbouring land, and the protection of water resources.

To infiltrate the entire storm event, the permeability coefficient *k* (m/s) should be between $10^{-5}$ and $10^{-2}$ m/s.

If *k* (m/s) is lower than $10^{-5}$, the most appropriate technical solutions with partial infiltration must be selected to maintain natural infiltration.

If *k* (m/s) is $10^{-3}$ m/s, a pre-treatment device or filter layer must be installed to prevent soil washing. In this case, infiltration wells are strictly prohibited.

**B. Discharge into the natural environment**

If it is found that drainage cannot technically be managed entirely through infiltration (which requires field measurements – see Chapter 11), the excess that cannot infiltrate should primarily be discharged into the natural environment.

The conditions for discharge into the natural environment are the same as for discharge into the public network.

**C. Discharge to the public network and shared flood/spreading areas**

Discharges and overflows must be directed to the shared stormwater management system of the local community (public network and flood/spreading areas), provided their capacity permits.

- Discharge

The permitted discharge may be defined as a throttled outflow, for example, one tenth of the runoff from a one-year rainfall event using the runoff coefficient of the baseline condition $\Psi_m = 0.1$. If the total project area (impervious area $A_{imp}$) is smaller than 0.1 ha, the throttled outflow may be set as an absolute value of 2 l/s (adapted from Breil, P. et al., 2009). In this case, the total outflow from smaller plots amounts to 20 l/s/ha.

- Overflow

Overflow must not be discharged into the sewer system for municipal and industrial wastewater, into a combined sewer system, or into the sewer network of state and municipal roads.

**D. Retention storage**

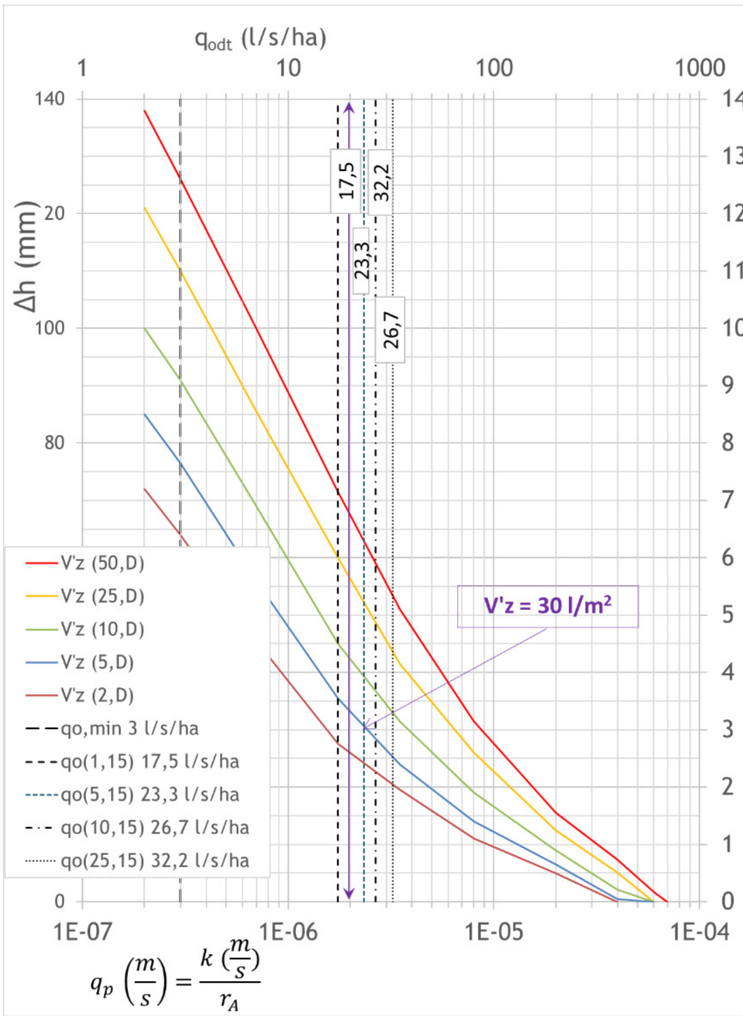
For development areas classified as "city centre / industrial / commercial areas" with an area of less than 1 hectare, a uniform retention requirement for rainfall events may be specified, for example, 30 l/m² of impervious surface ($V'_z$ = 3 m³/100 m² of $A_{imp}$) (example definition for Ljubljana – see Figure 21). This storage volume would be sufficient for discharge into the stormwater sewer system, if such a system were constructed for the area, with an acceptable flood return period of 30 years.

**E. Selection of the design rainfall event**

The selection of the return period for sizing the retention facility should be justified based on an applicable standard (see Table 6).

*Table 6. Criteria for selecting design rainfall events to determine an acceptable frequency of flooding (e.g. SIST EN 752-2).*

| Location | Design rainfall frequency, return period (years) |
|---|---|
| Rural areas | 1 in 1 |
| Residential areas | 1 in 20 |
| City centres / industrial / commercial areas | 1 in 30 |
| Underground railway/underpasses | 1 in 50 |




*Case 2:*

Retention storage: 30 l/m²

For 100 m² of impervious surface ($A_{imp}$ = 100 m²), a retention volume of $V_z$ = 3 m³ is required.

a)

With this storage volume, all 5-year rainfall events can be retained if the hydraulic conductivity is $k = 2.3 \times 10^{-5}$ m/s and the infiltration area is $A_p$ = 10 m² = $A_{imp}/10$.

b)

With this storage volume, all 30-year rainfall events can be retained if the hydraulic conductivity is $k = 7 \times 10^{-5}$ m/s and the infiltration area is $A_p$ = 10 m² = $A_{imp}/10$.

c)

With this storage volume, all 5-year rainfall events can be retained if the hydraulic conductivity is very low and the permitted discharge is $q_{thr}$ = 23.3 l/s/ha.

(ToolsD441_Design_curves_stormwater_1.xlsx)

*Figure 21. Illustration of the definition of the recommended retention volume for the desired level of safety (example for Ljubljana). $Q_{izp}$ (l/s/ha) = $q_p + q_{thr}$; $q_o$ = natural runoff; $A_{imp}/A_p = r_A$.*

# 8. Basis for “design for the final state of development”

## 8.1. General guidelines

The final state of development of a given spatial unit (spatial planning unit) indicates the arrangement of that unit once full utilisation has been achieved in accordance with the defined regulatory elements.

From a planning perspective, the final state of development is of interest primarily for the following reasons:

a) the degree of surface sealing and the amount of stormwater runoff that will need to be managed;

b) the amount of available unsealed (green) areas where infiltration surfaces and retention volumes can be provided;

c) the extent of roof surfaces with clean stormwater that can be infiltrated into the subsurface without special treatment;

d) the extent of heavily loaded paved traffic areas from which runoff will need to be infiltrated through biologically active soils of sufficient area;

e) whether prescribed or standard minimum setbacks of infiltration facilities from parcel boundaries and neighbouring structures will be sufficient, or whether additional setbacks will be required;

f) whether additional approvals and permits will be required for stormwater management measures that must be provided in the final development stage.

If, for the planned land use and final development, the regulatory elements do not ensure areas proportional to these requirements, difficulties and undefined delays may arise in the issuance of water consents, connection approvals, and approvals from neighbouring landowners.

## 8.2. Detailed guidelines for planning drainage for the final state of development

The possibility of using the Infiltration capacity map for planning interventions and drainage for the final state of development is demonstrated using the contributing catchment area of the Celovška road underpass in Ljubljana.

The example illustrates:

1. the location of the intervention area and its contributing catchment on the Infiltration capacity map;
2. the expected infiltration capacity and constraints in the area under consideration;
3. the selection of the design rainfall event;
4. options for reducing drainage costs by lowering the runoff coefficient;
5. verification of the zone of influence caused by perched groundwater;
6. the use of standard curves of specific retention volume to reduce drainage costs;
7. the infiltration influence zone and required setbacks.

Ad 1.) Location of the intervention and its catchment area on the Infiltration Capacity Map

For the example of planning for the final development state, we used a spatial planning unit (area 1,200 m²) designated for residential buildings, specifically for high-density residential development (blocks).

The intervention is located on the edge of the city centre, in an area with moderate infiltration capacity (Figure 22).

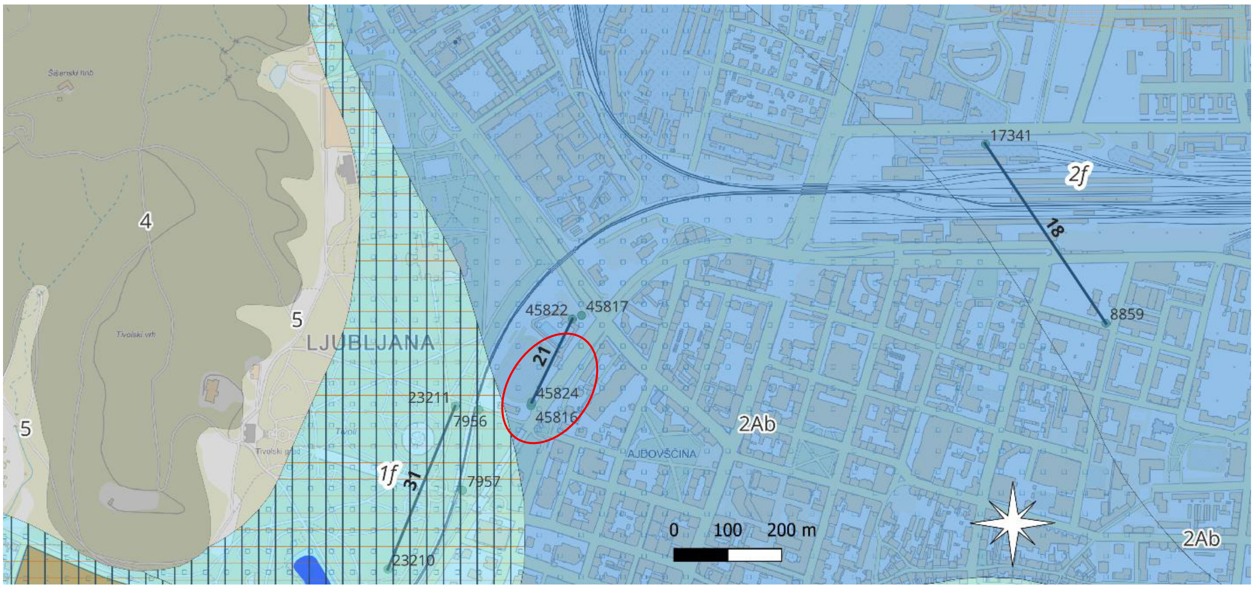


*Figure 22. Location of the case study on the infiltration capacity map (2Ab) – constraints (1f) – cross-section 21.*

Ad 2.) Expected infiltration capacity and limitations in the area

The spatial planning unit is situated in an area classified as "moderate infiltration capacity 2Ab" and "perched groundwater 1f", most commonly at depths of 3-6 m and 6-9 m, and less frequently at 9–12 m (Figure 16):

| Infiltration capacity | Limitations |
|---|---|
| 2: moderate infiltration capacity > $10^{-5}$ m/s<br>A: cover layer thickness < 3 m<br>B: depth to groundwater > 3 m | 1 – characteristic occurrence of perched groundwater<br>f – multiple horizons: most often at depths of 3-6 m and 6-9 m, less frequently at 9–12 m |

The expected thickness of the cover layer is less than 3 m. Perched groundwater is anticipated in several layers, but not at depths shallower than 3 m (1f). The main groundwater table is located deeper than 20 m (Figure 17).

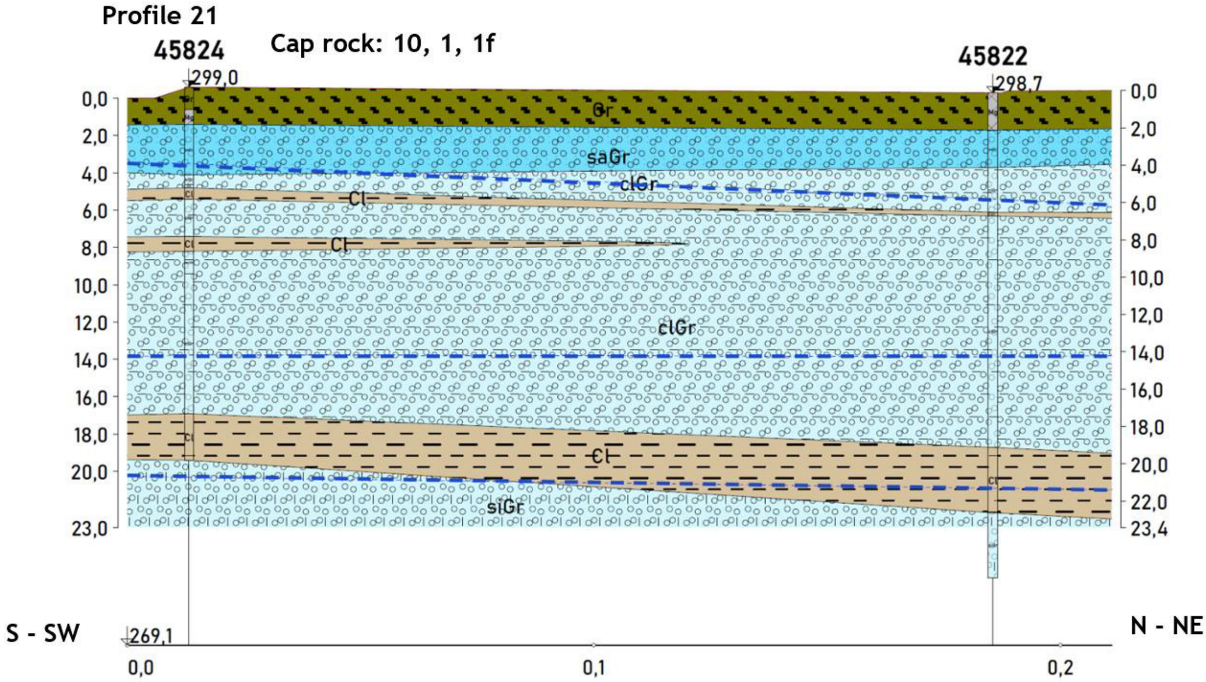



*Figure 23. Typical cross-section No. 21 through top layers with moderate infiltration capacity and occurrences of perched groundwater.*

Ad 3.) Selection of design storm

This is a residential neighbourhood in the city centre with moderate infiltration capacity. If overflow is possible, the site must retain a 5-year storm (Table 6), which is $q_{(5,\ 15)}$ = 233 l/s/ha (Table 1).

If overflow is not possible (e.g., if the sewer is overloaded or its capacity is unknown), the site must retain a 30-year storm (Table 6).

The Crossrisk model provides data for 25-year and 50-year storms. For a 30-year, 15-minute storm, we assume the average value, i.e., $q_{(30,\ 15)}$ ≈ 344 l/s/ha (Table 1).

Ad 4.) Options for reducing drainage volume by lowering the runoff coefficient

In this case, we assume that the final development fully utilises the assumed utilisation factors. Two possible design approaches are considered: A – very high runoff coefficients and B – very low runoff coefficients (Table 7). The runoff coefficient in design A is more than twice as high, at 0.74, compared to design B, where it is 0.34.

*Table 7. Example of the drainage design considered for the spatial planning unit in its final development state.*

A Runoff coefficient (Ψ) Max — 0.95 0.9 0.75 0.1

| SS - residential use | BF | FP_T | FP_L | USI | Runoff coefficient ($\Psi_m$) | Infiltration into the subsoil | Special drainage requirements |
|---|---|---|---|---|---|---|---|
| **free-standing blocks(villa block, block, tower block)** | **40** | **25** | **15** | **20** | **0.74** | **69%** | **31%** |
| outside a spatial node | 35 | 25 | 15 | 25 | 0.70 | 68% | 32% |
| higher density housing (blocks) | 35 | 20 | 15 | 30 | 0.66 | 73% | 27% |

B Runoff coefficient (Ψ) Min — 0.4 0.5 0.3 0.05

| SS - residential use | BF | FP_T | FP_L | USI | Runoff coefficient ($\Psi_m$) | Infiltration into the subsoil | Special drainage requirements |
|---|---|---|---|---|---|---|---|
| **free-standing blocks(villa block, block, tower block)** | **40** | **25** | **15** | **20** | **0.34** | **63%** | **37%** |
| **outside a spatial node** | 35 | 25 | 15 | 25 | 0.32 | 61% | 39% |
| **higher density housing (blocks)** | 35 | 20 | 15 | 30 | 0.30 | 67% | 33% |

In both examples shown, the assumed minimum required share of vegetated surface is considered, i.e., 20% or 240 m². In design B-, the runoff coefficient is close to 0.3, which is the optimal overall runoff coefficient when using blue-green infrastructure.

The peak runoff for the boundary condition of drainage design with overflow into the stormwater sewer system is $Q_{(5,15)}$ = 20.6 l/s in the first case and $Q_{(5,15)}$ = 9.5 l/s in the second case (Table 8).

*Table 8. Calculation of peak runoff for the case with overflow into the stormwater sewer system.*

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Multi-dwelling building** | 1200 | $m^2$ | q[n(years), T(minutes)] l/s/Ha | q[5,15] | 233 |
| | | **New situation A-** | | | | New situation |
| | **Surfaces** | **m2** | **Ψm** | | **A imp ($m^2$)** | outflow l/s |
| 40% | BF built-up area | 480 | 0.95 | sloping metal roof | 456 | 10.62 |
| 25% | FP-T paved external areas for transport, utilities and technical purposes | 300 | 0.9 | asphalt | 270 | 6.29 |
| 15% | FP-L paved external surfaces intended for living | 180 | 0.75 | paving with sealed joints | 135 | 3.15 |
| 20% | USI unsealed surface | 240 | 0.1 | meadow | 24 | 0.56 |
| | | | | | | |
| | **TOTAL** | **1200** | **0.74** | | **885** | 20.62 |
| | | | | | | |
| | | 1200 | | q[n(lyears), T(minutes)] l/s/Ha | q[5,15] | 233 |
| | **Multi-dwelling building** | **Baseline situation B-** | | | | Baseline situation |
| | **Surfaces** | $m^2$ | Ψm | | A imp ($m^2$) | outflow l/s |
| | BF built-up area | 480 | 0.4 | green roof | 192 | 4.47 |
| | FP-T paved external areas for transport, utilities and technical purposes | 300 | 0.5 | paving with open joints | 150 | 3.50 |
| | FP-L paved external surfaces intended for living | 180 | 0.3 | unbound gravel paving | 54 | 1.26 |
| | USI unsealed surface | 240 | 0.05 | meadow and garden | 12 | 0.28 |
| | | | | | | |
| | **TOTAL** | **1200** | **0.34** | | **408** | 9.51 |

The peak runoff for the boundary condition of drainage design without overflow into the stormwater sewer system is $Q_{(30,15)}$ = 30.4 l/s in the first case and $Q_{(30,15)}$ = 14.0 l/s in the second case (Table 9).

*Table 9. Calculation of peak runoff for the case without the possibility of overflow into the stormwater sewer system.*

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Multi-dwelling building** | 1200 | $m^2$ | q[n(years), T(minutes)] l/s/Ha | q[30,15] | 344 |
| | | **New situation A-** | | | | New situation |
| | **Surfaces** | **m2** | **Ψm** | | **A imp ($m^2$)** | outflow l/s |
| 40% | BF built-up area | 480 | 0.95 | sloping metal roof | 456 | 15.69 |
| 25% | FP-T paved external areas for transport, utilities and technical purposes | 300 | 0.9 | asphalt | 270 | 9.29 |
| 15% | FP-L paved external surfaces intended for living | 180 | 0.75 | paving with sealed joints | 135 | 4.64 |
| 20% | USI unsealed surface | 240 | 0.1 | meadow | 24 | 0.83 |
| | | | | | | 0.00 |
| | **TOTAL** | **1200** | **0.74** | | **885** | 30.44 |

| | | | | | |
|---|---|---|---|---|---|
| | 1200 | | q[n(lyears), T(minutes)] l/s/Ha | q[30,15] | 344 |
| **Multi-dwelling building** | **Baseline situation B-** | | | | Baseline situation |
| **Surfaces** | $m^2$ | Ψm | | A imp ($m^2$) | outflow l/s |
| BF built-up area | 480 | 0.4 | green roof | 192 | 6.60 |
| FP-T paved external areas for transport, utilities and technical purposes | 300 | 0.5 | paving with open joints | 150 | 5.16 |
| FP-L paved external surfaces intended for living | 180 | 0.3 | unbound gravel paving | 54 | 1.86 |
| USI unsealed surface | 240 | 0.05 | meadow and garden | 12 | 0.41 |
| | | | | | 0.00 |
| **TOTAL** | **1200** | **0.34** | | **408** | 14.04 |

Ad 5.) Verification of infiltration capacity on the plot

- Infiltration capacity based on permeability

For infiltration, we assume an infiltration area $A_p$ = 177 m², which is ¾ of the planned vegetated area. In Case A, the infiltration area represents 1/5 of the sealed surface of 885 m² ($r_A$ = 5). The infiltration capacity is $q_p$ = 20 l/s/ha. In Case B, the ratio between the sealed and infiltration area is $r_A$ = 2.3. The infiltration capacity is $q_p$ = 43.4 l/s/ha.

- Infiltration capacity based on water load

Approximately 1/3 of the water could infiltrate through dispersed infiltration via biologically active soil or other suitable treatment, provided the ratio between sealed and infiltration area is $r_A$ < 5 (Table 8).

In both cases, about 2/3 of the rainfall is suitable for direct infiltration into the groundwater.

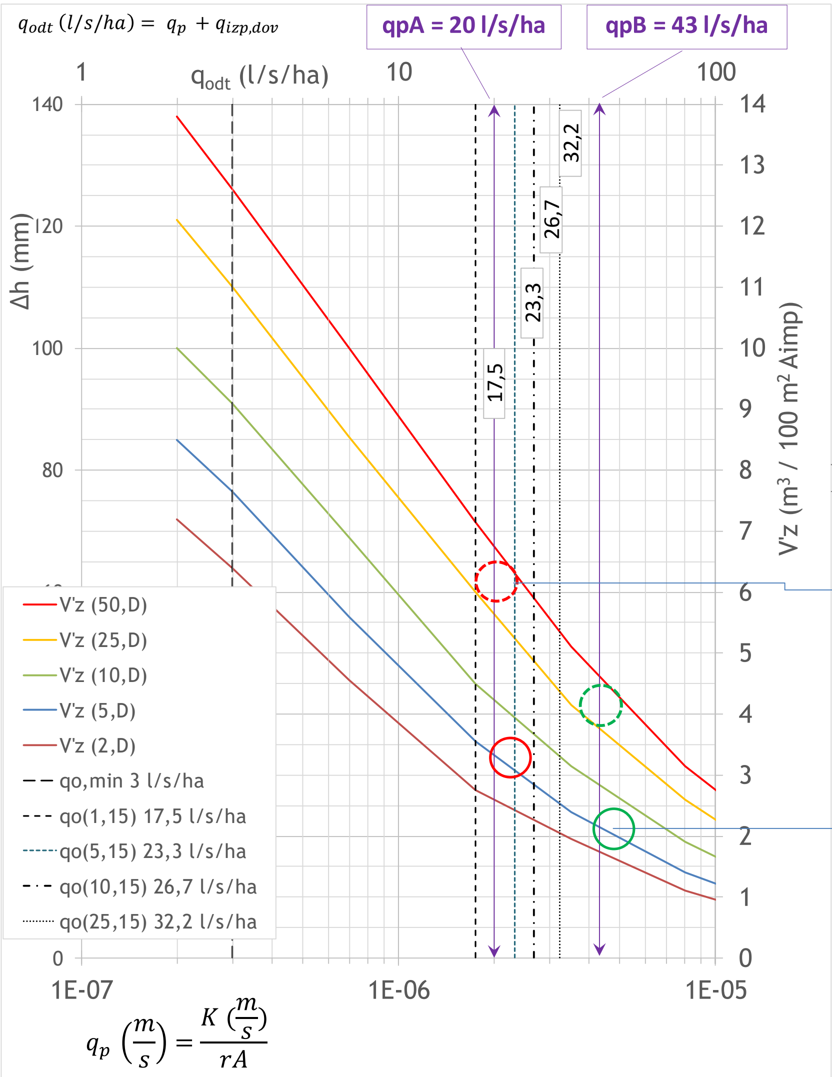
Ad 6.) Optimisation of retention volume and runoff coefficient

Case A – with a high runoff coefficient ($\Psi_m$ = 0.74), a retention volume of 54.9 m³ would be required if overflow to an off-site drain were not possible. If overflow were possible, a volume of 29.2 m³ would suffice (Figure 24 – red text). Water in the depression would be retained up to a maximum depth of 0.31 m or 0.17 m and would drain within 8.6 or 4.6 hours (Figure 24).

For case A, it would be reasonable to construct part of the retention underground, using the above-ground section only for exceptional rainfall events with a return period of 10 years or more.

Case B – with a very low runoff coefficient ($\Psi_m$ = 0.34) in a blue-green infrastructure solution, 17.1 m³ would be required if overflow were not possible. If overflow were possible, a volume of 9 m³ would suffice (Figure 24 – green text). Water in the depression would be retained up to a maximum depth of 0.1 m or 0.17 m and would drain within 8.6 or 4.6 hours (Figure 24).

For case B, the required volume could be provided entirely above ground and integrated almost invisibly into the vegetated part of the plot.




| A | | B |
|---|---|---|
| 1.00E-05 | k (m/s) | 1.00E-05 |
| 1200 | A ($m^2$) | 1200 |
| | Ψm | |
| 885 | Aimp | 408 |
| 177 | Ap sr ($m^2$) | 177 |
| 5.0 | rA | 2.3 |
| 2.00E-06 | qp (m/s) | 4.34E-06 |
| **20.0** | **qp (l/s/ha)** | **43.4** |
| 1.770 | Qp (l/s) | 1.770 |
| Vz' $m^3/100m^2$ | r(years) | Vz' $m^3/100m^2$ |
| 6.2 | 30 | 4.2 |
| 3.3 | 5 | 2.2 |
| Vz ($m^3$) | r(years) | Vz ($m^3$) |
| 54.9 | 30 | 17.1 |
| 29.2 | 5 | 9.0 |
| Water level | | |
| dH (m) | r(years) | dH (m) |
| 0.31 | 30 | 0.10 |
| 0.17 | 5 | 0.05 |
| Emptying | | |
| t(h) | r(years) | t(h) |
| 8.6 | 30 | 2.7 |
| 4.6 | 5 | 1.4 |

*Figure 24. Optimisation of the required retention volume in the selected example using standard curves for Ljubljana.*

- Verification of the calculation

The table below (Table 10) shows an example used to verify the calculation.

*Table 10. Verification of the calculation*

| SCENARIO A- | r=5 years | | 5 | 10 | 15 | 20 | 30 | 45 | 60 | 90 | 120 | 180 | 240 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **inflow surface 1** | | $m^2$ | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 |
| runoff coefficient | | runoff coef. | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 |
| inflow time | | min | 5 | 10 | 15 | 20 | 30 | 45 | 60 | 90 | 120 | 180 | 240 | 300 |
| rainfall | Crossrisk | l/s*ha | 400 | 283 | 233 | 192 | 156 | 122 | 100 | 78 | 64 | 50 | 41 | 36 |
| inflow | | l/s | 35.520 | 25.130 | 20.690 | 17.050 | 13.853 | 10.834 | 8.880 | 6.926 | 5.683 | 4.440 | 3.641 | 3.197 |
| infiltration | | l/s | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 | 1.770 |
| retained inflow | | l/s | 33.750 | 23.360 | 18.920 | 15.280 | 12.083 | 9.064 | 7.110 | 5.156 | 3.913 | 2.670 | 1.871 | 1.427 |
| required volume | | $m^3$ | 10.125 | 14.016 | 17.028 | 18.336 | 21.749 | 24.472 | 25.596 | 27.845 | 28.175 | 28.836 | 26.940 | 25.682 |
| **maximum required volume** | | $m^3$ | **28.84** | | | | | | | | | | | |
| **infiltration field (check dimensions of standard infiltration elements)** | | | | | | | | | | | | | | |
| length | 13.30 | m | | 888 | Aimp | | | | | | | | | |
| width | 13.35 | m | | 177.6 | Ap | | | | | | | | | |
| free depth | 0.162 | m | | 5 | rA | | | | | | | | | |
| infiltration volume | 28.84 | $m^3$ | | 20.0 | l/s/ha | | | | | | | | | |
| **INFILTRATION** | 177.6 | $m^2$ | | | | | | | | | | | | |
| permeability coef. | 0.00001 | m/s | 100.0 | l/s/ha | | | | | | | | | | |
| infiltration capacity | 1.770 | l/s | | | | | | | | | | | | |

In this way, we can search for the most favourable solution. For example, if the boundary condition is a retention volume $V_z \leq 18$ m³ and an infiltration area Ap = 177 m², with overflow to an off-site drain possible, the runoff coefficient should be $\Psi_m = 0.55$:

*Table 11. Example "C-" optimisation of drainage with the boundary condition of retention volume $Vz \leq 18$ m³.*

| | | | |
|---|---|---|---|
| | $k$ | 1,00E-05 | m/s |
| | $A$ | 1200 | $m^2$ |
| Boundary condition | $V_z$ | 18 | $m^3$ |
| | $A_p$ | 177 | $m^2$ |
| Adjustment | $\Psi_m$ | 0,55 | |
| | | | |
| Calculation | $A_{imp}$ | 660 | $m^2$ |
| | $r_A$ | 3,73 | |
| | $q_p$ | 2,68E-06 | m/s |
| | $V'_z$ | 2,7 | $m^3/100m^2$ |
| Target result | $V_z$ | 17,82 | $m^3$ |

The optimisation shows that the boundary condition of retention volume $V_z \leq 18$ m³ can be achieved with the given infiltration capacities and urban planning indicators using standard roof surfaces. Runoff can be sufficiently reduced if open traffic surfaces (FP_T) are constructed, for example, with pavements featuring open joints, and open living surfaces (FP_L) with unbound gravel paving, block paving with joints, or similar solutions.

*Table 12. Example "C-" optimised runoff coefficient for given urban planning indicators.*

| C Runoff coefficient (Ψ) Min | 0.9 | 0.5 | 0.3 | 0.05 | | | |
|---|---|---|---|---|---|---|---|
| **SS - residential use** | **BF** | **FP_T** | **FP_L** | **USI** | **Runoff coefficient (Ψm)** | **Infiltration into the subsoil** | **Special drainage requirements** |
| **free-standing blocks (villa block, block, tower block)** | **40** | **25** | **15** | **20** | **0.54** | **40%** | **23%** |
| **outside a spatial node** | 35 | 25 | 15 | 25 | 0.32 | 61% | 39% |
| **higher density housing (blocks)** | 35 | 20 | 15 | 30 | 0.30 | 67% | 33% |

Ad 7.) Zone of influence of infiltration – required vertical and horizontal setbacks

Due to the shallow perched groundwater table, we assess the potential rise in groundwater level beneath the infiltration field and the extent of the affected area.

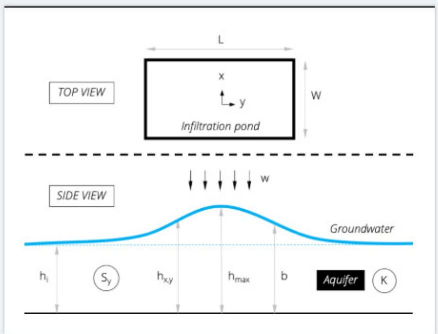
In Figure 25, for the considered Case A-, verification is shown using Hantush's analytical model.

The calculation assumes a scenario without possible overflow to an off-site drain. A 50-year, one-day rainfall event of 17 l/s/ha is considered.

If the perched groundwater layer during high water is 1 m thick, the groundwater level beneath the infiltration field would rise by a maximum of 0.71 m. It is therefore recommended that the bottom of the infiltration facility be 1.75 m above the highest groundwater level.

The affected area would not extend beyond the edge of the infiltration field at a noticeable height. At the edge of the field, the rise would be approximately 0.02 m (Figure 25).

INOWAS DSS https://dss.inowas.com/tools/T02




Qp = Ap × k
Qp = Aimp × qp

| | | | | | |
|---|---|---|---|---|---|
| Infiltration | w(r, D) | 1.70E-06 | m/s | 0.14688 | m/d |
| Basin length | L | 13.3 | m | 13.3 | m |
| Basin width | w | 13.30827 | m | 13.308271 | m |
| Initial water level | hi | 1 | m | 1 | m |
| Effective porosity | Sy | 0.15 | - | 0.15 | - |
| Permeability | K | 1.00E-05 | m/s | 0.864 | m/d |
| Infiltration time | t | 0.25 | h | 1 | d |
| | | | | | |
| Sealed surface | Aimp | 885 | m2 | | |
| rA | | 5 | | | |
| Infiltration capacity | qp | 2.00E-06 | m/s | | |
| Infiltration area | Ap | 177.0 | m2 | | |
| Possible infiltration volume | Qp | 1.77 | l/s/ha | | |
| Side of the square | a | 13.30 | m | 6.7 | a/2 |
| Retention volume | Vz | 0.00 | m3 | | |
| Water depth in the depression | H | 0.00 | m | | |
| Rainfall event | q (50, 1440) | 17 | l/s/ha | 1.70E-06 | m/s |
| | | | | | |
| Maximum rise in water level | hmax | 0.71 | m | | |
| Influence distance > 0.1 m | h0,1 | < 0 | m | | |

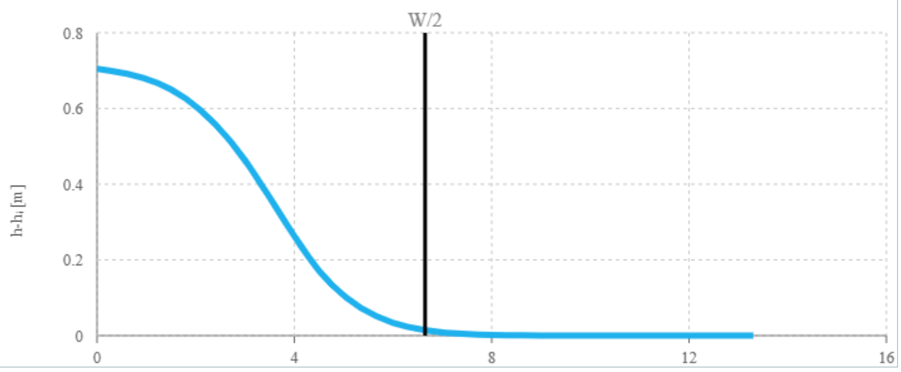



*Figure 25. Expected rise in groundwater level beneath the infiltration facility and the affected infiltration area.*

# 9. Basis for “Optimisation of measures”

- Optimisation at the initiative and conceptual design stage and during the process of obtaining opinions

At the lower limit of the permeability range for the moderate infiltration capacity class ($k = 1 \times 10^{-5}$ m/s), retention can be optimised by determining the most appropriate infiltration area and by defining the maximum permitted discharge into the stormwater sewer system or receiving water body.

Permeabilities within the moderate infiltration capacity class allow a favourable balance between infiltration area and retention volume. Even at the lower permeability limit of $k = 1 \times 10^{-5}$ m/s, it is possible to provide sufficient infiltration capacity to ensure that runoff from the site does not increase, or remains equivalent to the natural (pre-development) runoff conditions ($q_{o(r,D)}$).

- Optimisation during the permitting phase – improving investment security

Optimisation begins at the conceptual design stage, during pre-investment analysis, variant studies, and feasibility studies. The Infiltration Capacity Map therefore contains several pieces of information important for the geotechnical report and design, including depth to groundwater, occurrence of perched groundwater, thickness of confining layers, and permeability of the upper soil layers.

In subsequent planning stages, infiltration and retention systems must be dimensioned within the framework of the geotechnical report.

If perched groundwater, shallow bedrock, or surface slopes of 10° or more are present in the area under consideration, particular attention must be paid to the zone of influence of infiltration, appropriate spatial distribution of infiltration facilities, and safe setback distances.

Safe setbacks are important due to risks related to seepage, stability, internal erosion, the capacity of the on-site infiltration facility, and the capacity of existing neighbouring infiltration facilities.

- Planning field investigations of permeability and infiltration capacity

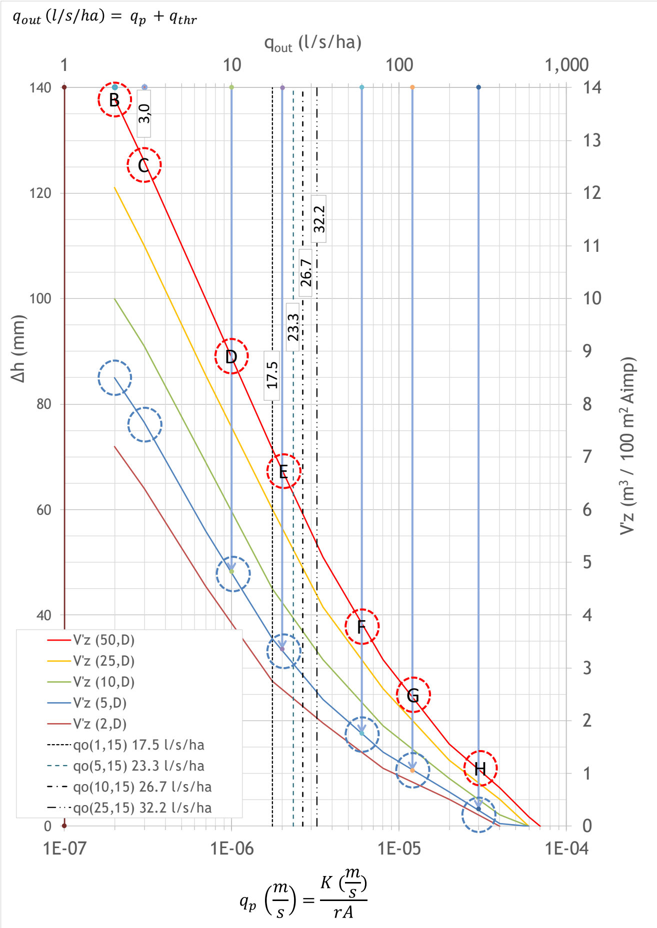
Accurate assessment of permeability can be crucial for cost-effective planning of drainage, infiltration, and retention measures. Accordingly, decisions must be made regarding how, to what extent, and at which stages field investigations and measurements will be carried out.

Using standard rainfall curves (*ToolsD441_Design_curves_stormwater_1.xlsx*), it is possible to assess the influence of permeability estimation accuracy on the calculated retention volume. These standard curves also provide a clear overview of the influence of the ratio between impervious and infiltration surfaces, as well as the impact of adjusting the runoff coefficient.

The example (Figure 26) represents a site with an area of 1,200 m², a total runoff coefficient $\Psi_m = 0.74$, and stormwater loading with an infiltration area equal to one fifth of the impervious surface. The example is provided in the tool *ToolsD441_RetentionVolumes_1.xlsx*.

Within the moderate permeability class ($k > 1 \times 10^{-5}$ m/s), the estimated retention volume for 5-year rainfall events may range from 30 to 3 m³ (examples E to H).

For optimal solutions, it is advisable to carry out field testing directly at the location and depth of the planned infiltration facility.



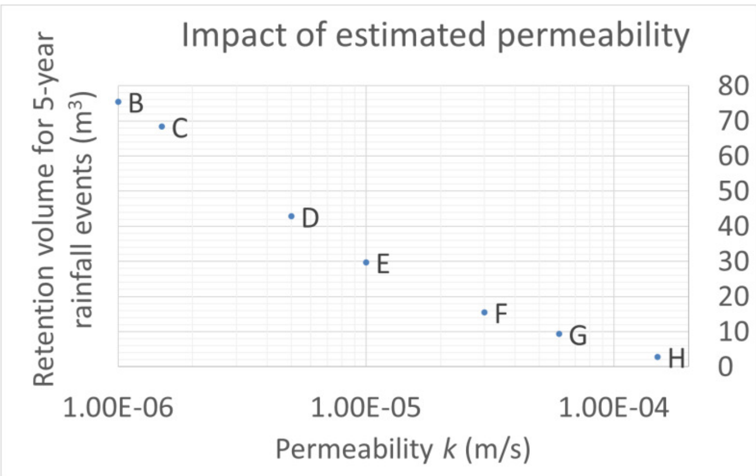

| | | | |
|---|---|---|---|
| A (m2) | 1200 | USI | 0.3 |
| Ψm | 0.74 | USI (m2) | 360 |
| Aimp | 888 | | |
| Ap sr (m2) | 177.6 | | |
| rA | 5.0 | | |

| Case | k (m/s) | qp (m/s) | **qodt (l/s/ha)** | Qp (l/s) |
|---|---|---|---|---|
| **A** | 5.00E-07 | 1.00E-07 | **1** | 0.089 |
| **B** | 1.00E-06 | 2.00E-07 | **2** | 0.178 |
| **C** | 1.50E-06 | 3.00E-07 | **3** | 0.266 |
| **D** | 5.00E-06 | 1.00E-06 | **10** | 0.888 |
| **E** | 1.00E-05 | 2.00E-06 | **20** | 1.776 |
| **F** | 3.00E-05 | 6.00E-06 | **60** | 5.328 |
| **G** | 6.00E-05 | 1.20E-05 | **120** | 10.656 |
| **H** | 1.50E-04 | 3.00E-05 | **300** | 26.640 |

| | r(years) = 30 | | r(years) = 5 | |
|---|---|---|---|---|
| Case | Vz' m³/100m² | Vz (m³) | Vz' m³/100m² | Vz (m³) |
| **A** | - | - | - | - |
| **B** | 13.8 | 122.5 | 8.5 | 75.5 |
| **C** | 12.6 | 111.9 | 7.7 | 68.4 |
| **D** | 8.9 | 79.0 | 4.82 | 42.8 |
| **E** | 6.75 | 59.9 | 3.35 | 29.7 |
| **F** | 3.85 | 34.2 | 1.75 | 15.5 |
| **G** | 2.45 | 21.8 | 1.05 | 9.3 |
| **H** | 1.1 | 9.8 | 0.32 | 2.8 |

| | Water hight r(years) = 30 | | Water hight r(years) = 5 | |
|---|---|---|---|---|
| Case | dH (m) on Ap | dH (m) on USI | dH (m) on Ap | dH (m) on USI |
| **A** | - | - | - | - |
| **B** | 0.69 | 0.34 | 0.43 | 0.21 |
| **C** | 0.63 | 0.31 | 0.39 | 0.19 |
| **D** | 0.45 | 0.22 | 0.24 | 0.12 |
| **E** | 0.34 | 0.17 | 0.17 | 0.08 |
| **F** | 0.19 | 0.09 | 0.09 | 0.04 |
| **G** | 0.12 | 0.06 | 0.05 | 0.03 |
| **H** | 0.06 | 0.03 | 0.02 | 0.01 |

| r (years) | 1* | 2* | 5 | 10 | 25 | 50 | 100 | 250 |
|---|---|---|---|---|---|---|---|---|
| 15 minutes | *175* | *199* | 233 | 267 | 322 | 367 | 411 | 478 |




The example describes a site with an area of 1,200 m² and a total runoff coefficient $\Psi_m$ = 0.74, which receives stormwater runoff with an infiltration area equal to one fifth of the impervious surface.

Within the moderate permeability class ($k > 1 \times 10^{-5}$ m/s), the estimated retention volume for 5-year rainfall events may range from 30 to 3 m³ (examples E to H).

For optimal solutions, it is advisable to conduct testing directly at the location and at the depth of the planned infiltration facility.

*Figure 26. Example of the impact of permeability estimation on the assessment of the required retention volume for stormwater infiltration (ToolsD441_RetentionVolumes_1.xslx).*

# 10. Transfer and use of the map in spatial planning

## 10.1. Decision-making

A key aspect in deciding on the development of a drainage concept is determining how responsibility for stormwater management is shared between the community and individual investors. An optimal balance between these two parties results in the greatest cost efficiency. Placing too great a burden on either side does not allow for sustainable and resilient management. The common interest is the security of investments.

The community seeks solutions to address the cumulative impacts of drainage across the entire functional urban area. The most pronounced cumulative impact occurs at the discharge points of combined water volumes into the river. Other important aspects span physical to social domains (e.g. erosion, replenishment of water resources, ecosystem conservation, equal opportunities for all spatial users).

An individual investor, on the other hand, seeks solutions that ensure optimal use of the parcel, building safety, and other essential requirements that the structure must meet.

## 10.2. Share of the parcel to be allocated for infiltration

The share of the parcel that must be allocated for infiltration depends on the hydraulic conductivity coefficient *k*, the overall runoff coefficient of the site $\Psi_m$, the target infiltration capacity $q_p$ (Equations 12, 13, 14), and the minimum setback distances.

As a baseline assumption, the target infiltration capacity qp is taken to be equal to the natural runoff $q_0$, for example, the runoff from a flat grass-covered surface with an overall runoff coefficient $\Psi_m = 0.1$.

In this way, the retention volume required to manage peak runoff from a rainfall event would be the same as for a site with very low infiltration capacity, where instead of infiltration, a minimum discharge to the environment, a surface water body, or the sewer system must be provided, so that peak instantaneous runoff does not exceed pre-development conditions.

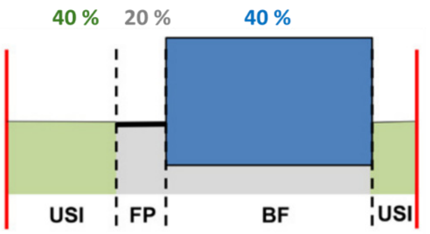
If $k > 5 \times 10^{-6}$ m/s, the minimum area required for retention and infiltration may already be lower than the minimum recommended factor of vegetated surfaces.

$$\frac{A_p}{A} = dA_p = \frac{\Psi_m \times q_0 \times 10^{-7}}{k} \quad (16)$$

**For the actual area, minimum setback distances must also be verified.**

**Minimum share of plot for infiltration**

For permeability $k > 5 \times 10^{-6}$ m/s, the minimum area required for infiltration ($A_p$, min) is smaller than the predicted share of unsealed surface.




$$\frac{A_p}{A} = dA_p = \frac{\Psi_m \times q_0 \times 10^{-7}}{k}$$

| | | | |
|---|---|---|---|
| r (let) | 10 | 10 | 10 |
| q₀(r,D) × 0,1 (l/s/ha) | 26,7 | 26,7 | 26,7 |
| Ψm | 0,3 | 0,5 | 0,8 |
| K (m/s) | dAp | dAp | dAp |
| 5,00E-07 | 160% | 267% | 427% |
| 1,00E-06 | 80% | 134% | 214% |
| 5,00E-06 | 16% | 27% | 43% |
| 1,00E-05 | 8% | 13% | 21% |
| 5,00E-05 | 2% | 3% | 4% |
| 1,00E-04 | 1% | 1% | 2% |
| 5,00E-04 | 0,2% | 0,3% | 0,4% |

The infiltration area Ap would exceed the parcel size A.
The infiltration area Ap would exceed the unsealed surface (USI).

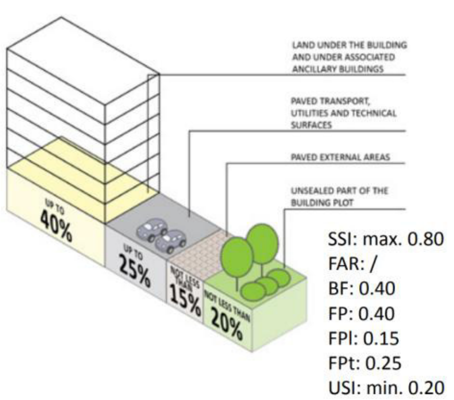
**$k > 5 \times 10^{-6}$ m/s ≈ Ap, min < USI**

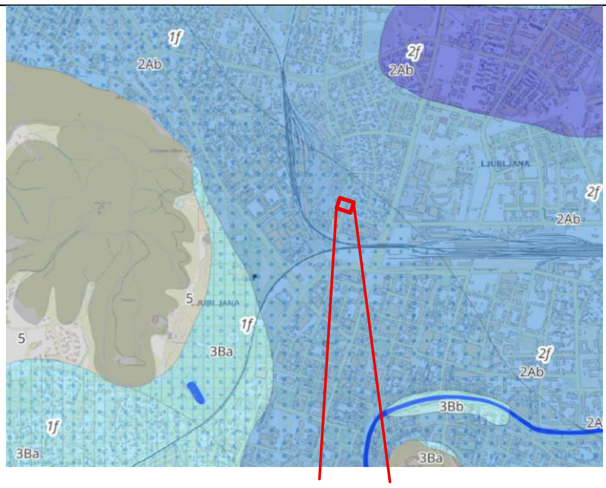
*Figure 27. Minimum share of plot for infiltration.*

- Example of using vegetated surfaces for infiltration and retention

The example (Figures 28 and 26) shows a building plot with a multi-residential building located in an area with moderate infiltration capacity (2Ab), where infiltration of the entire rainfall volume is possible on the planned vegetated surface USI of 240 m², with retention of a 30-year rainfall event corresponding to a water depth of $dH$ = 0.25–0.04 m ($1 \times 10^{-5} < k$ (m/s) $< 1.5 \times 10^{-4}$).

**Free-standing block in a spatial node**




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Multi-dwelling building** | 1200 | m² | q[n(years), T(minutes)] l/s/Ha | q[30,15] | 344 |
| | | | **New situation A-** | | | | New situation |
| | | **Surfaces** | **m2** | **Ψm** | | **A imp (m²)** | outflow l/s |
| BF | 40% | BF built-up area | 480 | 0,95 | sloping metal roof | 456 | 15,69 |
| FP-T | 25% | FP-T paved external areas for transport, utilities and | 300 | 0,9 | asphalt | 270 | 9,29 |
| FP-L | 15% | FP-L paved external surfaces intended for living | 180 | 0,75 | paving with sealed joints | 135 | 4,64 |
| USI | 20% | USI unsealed surface | 240 | 0,1 | meadow | 24 | 0,83 |
| | | | | | | | 0,00 |
| | | **TOTAL** | **1200** | **0,74** | | **885** | 30,44 |

| Case | k (m/s) | qp (m/s) | qout (l/s/ha) | Qp (l/s) |
|---|---|---|---|---|
| A | 5.00E-07 | 1.00E-07 | 1 | 0.089 |
| B | 1.00E-06 | 2.00E-07 | 2 | 0.178 |
| C | 1.50E-06 | 3.00E-07 | 3 | 0.266 |
| D | 5.00E-06 | 1.00E-06 | 10 | 0.888 |
| E | 1.00E-05 | 2.00E-06 | 20 | 1.776 |
| F | 3.00E-05 | 6.00E-06 | 60 | 5.328 |
| G | 6.00E-05 | 1.20E-05 | 120 | 10.656 |
| H | 1.50E-04 | 3.00E-05 | 300 | 26.640 |

| Vz | Retention volume | | | |
|---|---|---|---|---|
| | r(years) = 50 | | r(years) = 5 | |
| Case | Vz' m³/100m² | Vz (m³) | Vz' m³/100m² | Vz (m³) |
| A | - | - | - | - |
| B | 13.8 | 122.5 | 8.5 | 75.5 |
| C | 12.6 | 111.9 | 7.7 | 68.4 |
| D | 8.9 | 79.0 | 4.82 | 42.8 |
| E | 6.75 | 59.9 | 3.35 | 29.7 |
| F | 3.85 | 34.2 | 1.75 | 15.5 |
| G | 2.45 | 21.8 | 1.05 | 9.3 |
| H | 1.1 | 9.8 | 0.32 | 2.8 |

| dH | Water hight | | | |
|---|---|---|---|---|
| | r(years) = 50 | | r(years) = 5 | |
| Case | dH (m) on Ap | dH (m) on USI | dH (m) on Ap | dH (m) on USI |
| A | - | - | - | - |
| B | 0.69 | 0.51 | 0.43 | 0.31 |
| C | 0.63 | 0.47 | 0.39 | 0.28 |
| D | 0.45 | 0.33 | 0.24 | 0.18 |
| E | 0.34 | 0.25 | 0.17 | 0.12 |
| F | 0.19 | 0.14 | 0.09 | 0.06 |
| G | 0.12 | 0.09 | 0.05 | 0.04 |
| H | 0.06 | 0.04 | 0.02 | 0.01 |


*Figure 28. Example of the use of unsealed surfaces for infiltration and retention.*

## 10.3. Facilitating the preparation and issuance of opinions and consents

The most important factor in simplifying procedures for obtaining consents is having a clear understanding, in advance, of what is assessed during consent-granting procedures and at any later stage during use or operation.

Consents are required in three key procedures:

- water opinion in the preparation of spatial planning documents;
- consent for connection;
- water consent in the building permit issuance process.

The more clearly solutions are defined in the spatial planning document, the easier it is to obtain consents and the faster the administrative procedures.

From the perspective of drainage and infiltration, it is crucial that the following checks are carried out at the level of the spatial planning document or spatial unit for the final state of development, and subsequently in further procedures at the level of the building plot prior to obtaining a building permit:

- <u>All areas</u>
  - whether optimisation of the runoff coefficient is demonstrated;
  - whether the permeability and infiltration capacity of the site are defined;
  - whether the return period for allowable flooding is specified;
  - whether the quantity of stormwater is assessed according to pollution load (roof runoff, runoff from paved open residential areas, runoff from open traffic areas);
  - whether the method of infiltration is defined according to the planned type and pollution load of stormwater;
  - whether the infiltration area and required retention volume are assessed;
  - whether the potential occurrence of perched groundwater is checked;
  - whether the significance of groundwater level rise beneath infiltration facilities and the extent of the influence zone for rises exceeding $dH > 0.1$ m are assessed.
- <u>Moderate infiltration capacity</u>
  - whether the overflow location and the return period of allowable overflow are defined.
- <u>Lower infiltration capacity</u>
  - whether the possibility of discharge (throttled outflow – flow restrictor) and the discharge location are provided;
  - whether the permitted discharge rate is defined.
- <u>Shallow groundwater table or shallow bedrock</u>
  - whether the zone of influence of distributed drainage with respect to neighbouring land parcels and structures is calculated;
  - whether the need for special setback distances is explicitly defined;
  - whether minimum infiltration setbacks are calculated with regard to seepage risk, mutual influence between neighbouring infiltration facilities, and the potential for internal erosion on slopes and terraces.

# D. RECOMMENDATIONS FOR A MORE DETAILED ASSESSMENT OF PERMEABILITY

## 11. Field measurements

Several types of field tests are available for assessing the infiltration rate of natural soils, including the use of permeameters or infiltrometers, infiltration tests, and empirical correlations between grain size distribution and the permeability coefficient (hydraulic conductivity). There are certain differences among these methods.

Using a Guelph permeameter and a double-ring infiltrometer, we can assess the vertical movement of water through the bottom of the test area. The outer ring reduces lateral water movement in the soil. During infiltration tests, on the other hand, the water is moving through both the bottom and the sides of the test area.

To verify the infiltration rate of natural soils during planning, it is strongly recommended to carry out infiltration tests using methods for determining hydraulic conductivity under saturated conditions (TRCA, 2012), such as the standardised double-ring infiltrometer method (ASTM, 2009).

In general, infiltration tests should not be performed during rainfall, within 24 hours after major rainfall events (>15 millimetres), or when the temperature is below freezing (TRCA, 2012). The optimal time for conducting infiltration tests is April and May, when infiltration is likely to be reduced due to saturated conditions (TRCA, 2012). If infiltration tests are carried out between 1 June and 31 December, a 24-hour pre-soaking is recommended to simulate saturated field conditions (TRCA, 2012). Pre-soaking is not required for tests using a permeameter or infiltrometer.

Alternatively, other permeability testing methods that provide values of saturated hydraulic conductivity can be used, such as equations developed by Elrick and Reynolds, or similar methods for calculating hydraulic and saturated hydraulic conductivity (TRCA, 2012).

At least one test should be performed at the intended depth of the bottom of the infiltration system, with additional tests in each other soil layer up to 1.5 metres below the proposed bottom of the infiltration system (TRCA, 2012). It is recommended to perform at least two tests in each test area. If the results of the first two tests differ significantly, additional tests are required. To determine the average infiltration rate for each soil layer after multiple tests, the geometric mean is used (TRCA, 2012).

### 11.1. Double-Ring Method

The double-ring infiltrometer (DRI) is a cylindrical infiltrometer used to measure infiltration under saturated conditions following a standardised method (ASTM, 2009). Two metal rings, the inner (approximately 30 cm) and the outer (approximately 60 cm), are inserted into the soil to a selected depth, usually up to 10 cm. The outer ring reduces lateral outflow and ensures primarily vertical water movement. Both rings are filled with water to a chosen height (5–15 cm), and during the test, the water level in the rings is kept constant by adding water as needed. The infiltration rate is calculated based on the amount of water added at specific time intervals. The measurement continues until steady-state infiltration is reached, usually for at least one hour, and longer for less permeable soils. The saturated hydraulic conductivity can be estimated using Equation (3) (Arriaga et al., 2010; Bodhinayake et al., 2004; USDA, 2014), which is based on infiltration principles from infiltrometers described in studies by Reynolds and Elrick (1990) and Youngs et al. (1995):

$$K_s = \frac{q_s}{\left(\left(\frac{H}{B_1 d + B_2 a}\right) + \left(\frac{1}{\alpha(B_1 d + B_2 a)}\right) + 1\right)} \quad (19)$$

where $K_s$ is the saturated hydraulic conductivity (cm/s), $q_s$ is quasi-steady infiltration rate (cm/s), $H$ is the steady depth of ponded water in ring (cm), $a$ is radius of the inner ring (cm), $d$ is depth of ring insertion into soil (cm), $B_1$ and $B_2$ are dimensionless quasi-empirical constants (for $d$ > 3 and $H$ > 5 cm: $B_1$ = 0,316π, $B_2$ = 0,184π),$\alpha$ is the soil macroscopic capillary length (1/cm).

## 11.2. Infiltration tests

Infiltration tests are conducted in an excavation of arbitrary size, for example, 1 m³, however, the dimensions of the excavation sides are important for accurate calculation of hydraulic conductivity. The hydraulic conductivity can be calculated using the constant-head infiltration method (Brenčič, 2011) or the falling-head method, where water is poured into the excavation and the water level decline is monitored (NE.CH, 2018; Prestor, 2021).

In constant-head infiltration test method, water is poured into the excavation at a constant flow rate, and the height at which the water level stabilises above the bottom of the excavation is measured. The selected flow rate must allow complete infiltration, and water is added until the water level becomes fully stable (i.e., neither rising nor falling). The hydraulic conductivity (m/s) is calculated from the stationary part of the test using Equations (4) and (5) (Brenčič, 2011):

$$K_s = \frac{Q}{A} \quad (20)$$

$$A = a \cdot b + 2 \cdot (a + b) \cdot h \quad (21)$$

Where $K_s$ is saturated hydraulic conductivity (m/s), $Q$ is constant inflow of water into the excavation (m³/s), $A$ is wetted surface area of the excavation (m²), $a$ is excavation length (m), $b$ is excavation width (m), $h$ is stabilised water height above the bottom during constant inflow Q (m).

In falling-head infiltration test method, water is poured into the excavation to the desired height, and then the decrease in water level over time is measured. Hydraulic conductivity is calculated using Equations (6) and (7):

$$k = \frac{-C}{60 \cdot (t_2 - t_1)} \cdot ln\left(\frac{h_2 + C}{h_1 + C}\right) \quad (22)$$

$$C = \frac{a \cdot b}{2 \cdot (a + b)} \quad (23)$$

Where $k$ is hydraulic conductivity (m/s), $t_1$ is start time of water level drop measurement (min), $t_2$ is end time of water level drop measurement (min), $h_1$ is water height above the bottom at time $t_1$, $h_2$ is water height above the bottom at time $t_2$, $a$ is excavation length (m), $b$ is excavation width (m), $C$ is ratio between the area and perimeter of the excavation bottom (m).

## 11.3. Evaluation of measurement errors

**Evaluation of measurement errors and their impact on the calculated value of the permeability coefficient using infiltration and ponded infiltration tests.**

An example of assessing the potential influence of measurement errors on the calculated hydraulic conductivity is provided in the appendices (Chapter 17.1). Calculations show that the largest possible errors in determining hydraulic conductivity (on the order of 1 × 10⁻⁵ m/s) are likely due to inaccuracies in recording the excavation dimensions, which are also considered the most realistic source of error. Errors associated with measurements of discharge and water level using a pressure probe are significantly smaller (on the order of $1 \times 10^{-6}$ m/s).

# 12. TOOLS

1. Excel table: ToolsD441_Design_curves_stormwater_1
2. Excel table: ToolsD441_RetentionVolumes_1

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# 14. APPENDICES

## 14.1. Assessment of the impact of possible measurement errors

**Infiltration tests with a double ring**

Errors may occur when measuring the drawdown of water level in the Mariotte device and when maintaining a constant water level in the ring.

The water level in the Mariotte device is measured using a pressure probe accurate to one tenth of a millimetre, for example, 1000.0 mm. If an error of 0.1% occurs over a 1 m water column, this corresponds to an absolute error of 1 mm. An error of 1% over the same water column corresponds to an absolute error of 10 mm (i.e. 1 cm).

We calculated how this error could affect the reliability of the calculated hydraulic conductivity values.

| Effect of errors in measuring the water-level drawdown in the Mariotte device per unit time (final curve) | | | | | | |
|---|---|---|---|---|---|---|
| parameter | unit | original | ds -1cm | ds +1cm | ds -1mm | ds +1mm |
| qs | cm/s | 0.00350 | 0.00323 | 0.00377 | 0.00348 | 0.00353 |
| H | cm | 5 | 5 | 5 | 5 | 5 |
| a | cm | 15.7 | 15.7 | 15.7 | 15.7 | 15.7 |
| d | cm | 5 | 5 | 5 | 5 | 5 |
| B1 | - | 0.9927 | 0.9927 | 0.9927 | 0.9927 | 0.9927 |
| B2 | - | 0.5781 | 0.5781 | 0.5781 | 0.5781 | 0.5781 |
| alfa | /cm | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Ks | cm/s | 3.69E-03 | 3.40E-03 | 3.97E-03 | 3.66E-03 | 3.72E-03 |
| **Ks** | **m/s** | **3.69E-05** | **3.40E-05** | **3.97E-05** | **3.66E-05** | **3.72E-05** |
| error | m/s | | **-2.86E-06** | **2.86E-06** | **-2.86E-07** | **2.86E-07** |

If the actual drawdown in the Mariotte device is smaller or larger by 1 mm (ds-1mm, or ds+1mm), the error in the calculated hydraulic conductivity is approximately $\pm 3 \times 10^{-7}$ m/s. If the actual drawdown in the Mariotte device is smaller or larger by 1 cm (10 mm; i.e. ds-1cm, or ds+1cm), the error in the calculated hydraulic conductivity is approximately $\pm 3 \times 10^{-6}$ m/s, which does not significantly affect the calculated K, which is in the order of $3 \times 10^{-5}$ m/s.

Next, we evaluate the possible error while maintaining a constant water level in the ring. We consider scenarios where the actual water level in the ring is 0.5 cm or 1 cm higher or lower than the intended level (5 cm). Based on the calculations, the error in the calculated hydraulic conductivity is in the order of up to $\pm 3 \times 10^{-6}$ m/s, which does not significantly affect the calculated K, which is in the order of $3 \times 10^{-5}$ m/s.

| Effect of errors in maintaining a constant water level in the ring | | | | | | |
|---|---|---|---|---|---|---|
| parameter | unit | original | dH -0.5cm | dH +0.5cm | dH -1cm | dH +1cm |
| qs | cm/s | 0.00350 | 0.00350 | 0.00350 | 0.00350 | 0.00350 |
| H | cm | 5 | 4.5 | 5.5 | 4 | 6 |
| a | cm | 15.7 | 15.7 | 15.7 | 15.7 | 15.7 |
| d | cm | 5 | 5 | 5 | 5 | 5 |
| B1 | - | 0.9927 | 0.9927 | 0.9927 | 0.9927 | 0.9927 |
| B2 | - | 0.5781 | 0.5781 | 0.5781 | 0.5781 | 0.5781 |
| alfa | /cm | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Ks | cm/s | 3.69E-03 | 3.83E-03 | 3.56E-03 | 3.99E-03 | 3.43E-03 |
| **Ks** | **m/s** | **3.69E-05** | **3.83E-05** | **3.56E-05** | **3.99E-05** | **3.43E-05** |
| error | m/s | | **-1.44E-06** | **1.33E-06** | **-2.99E-06** | **2.57E-06** |

**Infiltration tests in excavations using the constant-head method**

We assume possible errors in measuring inflow of water with a bucket and timer, as well as in measuring the dimensions of the excavation for the infiltration test.

The cumulative effect of errors in time measurement (±0.5 s and ±1 s) and water volume in the bucket (±0.1 L and ±0.2 L) indicates that the resulting error in the calculated hydraulic conductivity is in the order of up to $\pm 2{,}4 \times 10^{-6}$ m/s.

| Effect of cumulative time and volume measurement errors on the calculation of K | | | | | | |
|---|---|---|---|---|---|---|
| parameter | unit | original | -0.5s&+1dcl | +0.5s&-1dcl | -1s&+2dcl | +1s&-2dcl |
| K | m/s | 4.96E-05 | 5.07E-05 | 4.84E-05 | 5.19E-05 | 4.73E-05 |
| **error** | **m/s** | | **1.18E-06** | **-1.15E-06** | **2.38E-06** | **-2.29E-06** |

On the other hand, we found that errors resulting from incorrectly recorded excavation dimensions are significantly larger.

If all measured dimensions (length and width of the excavation and water column height) were incorrect by ±10 cm, the error in the calculated hydraulic conductivity would be up to $\pm 1.6 \times 10^{-5}$ m/s.

If all measured dimensions (length and width of the excavation and water column height) were incorrect by ±20 cm, the error in the calculated hydraulic conductivity would be up to $\pm 4.1 \times 10^{-5}$ m/s.

| Effect of errors in measuring excavation dimensions on the calculation of K | | | | | | |
|---|---|---|---|---|---|---|
| parameter | unit | original | -10 cm | +10 cm | -20 cm | +20 cm |
| K | m/s | 4.96E-05 | 6.54E-05 | 3.89E-05 | 9.03E-05 | 3.14E-05 |
| **error** | **m/s** | | **1.58E-05** | **-1.07E-05** | **4.08E-05** | **-1.82E-05** |

**Infiltration tests in excavations using the falling-head method**

We assume possible errors in measuring the dimensions of the excavation (±10 cm or ±20 cm) for the infiltration test, as well as in measuring the drawdown of water level in the excavation (±10 cm or ±20 cm).

| Cumulative effect of errors in excavation dimension measurements and water-level drawdown measurements on the calculation of K | | | | | | |
|---|---|---|---|---|---|---|
| parameter | unit | original | -10cm&+10cm | +10cm&-10cm | -20cm&+20cm | +20cm&-20cm |
| K | m/s | 1.4E-05 | 7.3E-06 | 2.2E-05 | 2.5E-06 | 3.2E-05 |
| **error** | **m/s** | | **-6.4E-06** | **8.2E-06** | **-1.1E-05** | **1.9E-05** |

The cumulative impact on the calculation of hydraulic conductivity indicates a possible error of up to $\pm 1.9 \times 10^{-5}$ m/s.