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MAURICE

Deliverable 1.5.2
Technical Report
Key tools enabling sponge cities

Version 3

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CONTENT LIST

1. Sponge city needs

Urban areas are particularly vulnerable to climate change due to their dense populations, extensive infrastructure networks, and reliance on centralised water systems. The increasing impacts of climate change heighten the risk of frequent flooding events alternating with droughts and freshwater shortages. The long-established interaction between natural groundwater systems and artificial water bodies is increasingly being disrupted. As a consequence, cities are facing substantial water management challenges related a.o. to water quality, water availability, and groundwater-induced land subsidence.

Groundwater levels are already decreasing in many aquifers globally. However, groundwater storage is relatively less sensitive to seasonal or multiyear climatic variability than other groundwater linked variables such as recharge and discharge, reacting slower to variation in precipitations events than surface water bodies. But groundwater storage depletion is in fact deleterious for livelihood and ecological sustainability, while reducing the possible discharge to surface waters as streams and lakes and enhancing the risks of land subsidence. The influence of climate change on groundwater quality may also be associated with increased leaching of contaminants under warmer climatic conditions.

The sponge city concept is an innovative urban water management approach designed to address the challenges posed by climate change. The idea is to transform urban areas into sponges that can absorb, store, and reuse rainwater effectively, thereby reducing the strain on traditional drainage systems and improving water resilience. Sponge cities integrate blue-green infrastructure and nature-based solutions, such as permeable pavements, green roofs, rain gardens, and constructed wetlands, to enhance water infiltration, storage, and purification. By replicating natural hydrological processes, sponge cities aim to mitigate urban flooding, improve water quality, and ensure sustainable urban water resources.

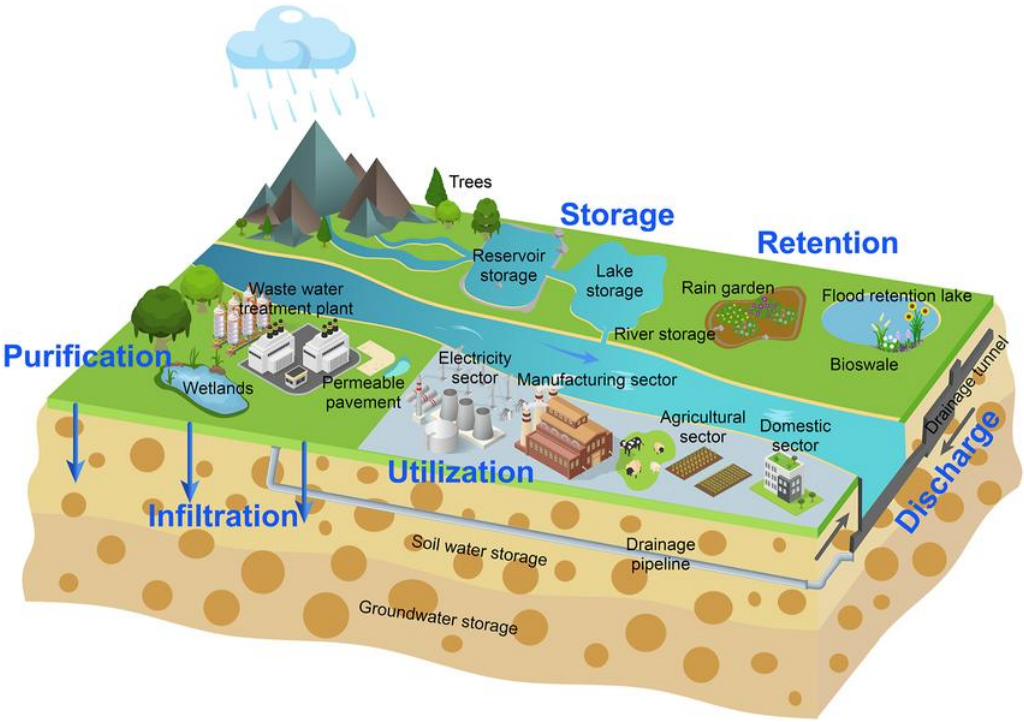


Figure 1-1: The six hydrological processes in sponge city design[1]

[1] Liu, Qianhui & Cui, Wenhui & Tian, Zhan & Tang, Yingdong & Tillotson, Martin & Liu, Junguo. (2022). Stormwater Management Modeling in "Sponge City" Construction: Current State and Future Directions. Frontiers in Environmental Science. 9. 10.3389/fenvs.2021.816093.

The MAURICE project, which stands for "Management of Urban Water Resources in Central Europe Facing Climate Change," is a transnational initiative aimed at increasing the resilience of urban water systems to climate change-related pressures. The MAURICE project aligns closely with the principles of the sponge city concept by incorporating nature-based solutions and blue-green infrastructure into its urban water management strategies. The project aimed to enhance the resilience of urban water systems to climate change-related pressures, such as declining groundwater levels and excessive water accumulation during short periods. By leveraging sponge city principles, MAURICE focused on sustainable water management practices that mimic natural hydrological processes to address these challenges.

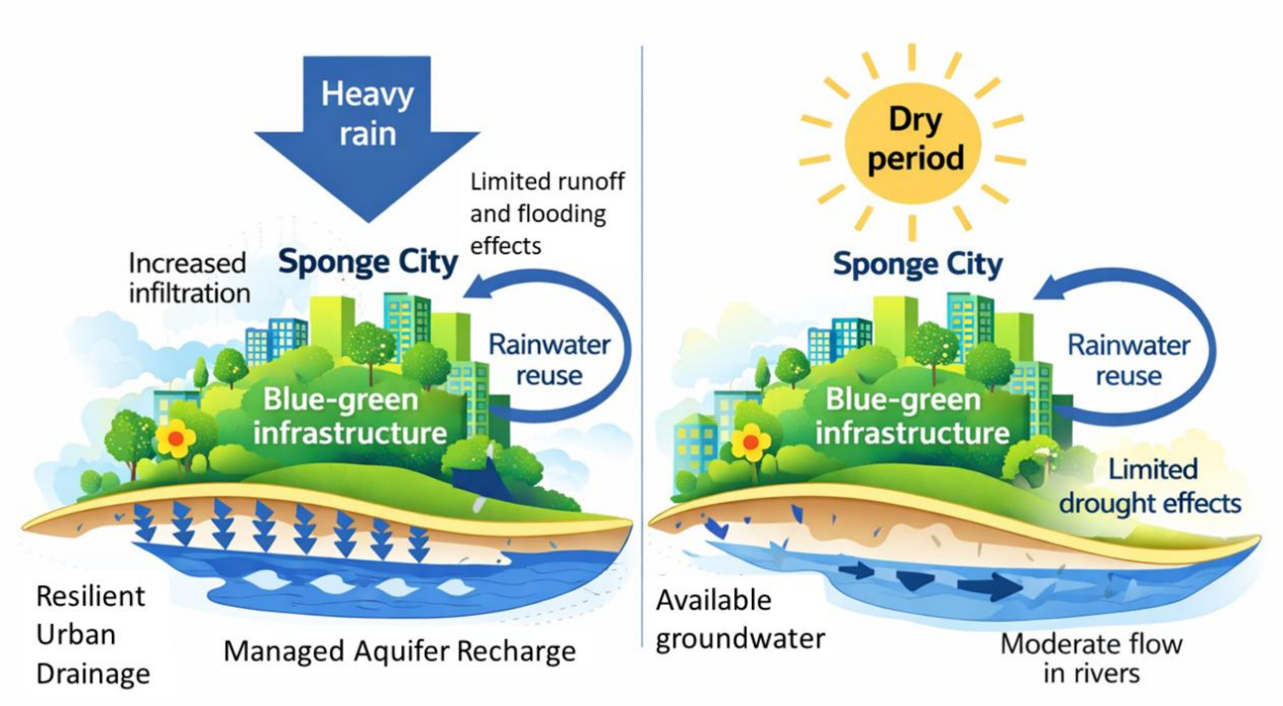


Figure 1-2: Sponge City (Image created by MAURICE with Copilot)

Key sponge city principles of the MAURICE project:

Blue-Green Infrastructure:

The MAURICE project emphasizes the implementation of blue-green infrastructure, which is a core element of the sponge city concept. BGI is a strategic, nature-based planning approach that combines water management ("blue") and green space ("green") to enhance urban resilience and sustainability. For example, in Jaworzno, the project targets urban development by delineating vulnerability zones and providing guidelines for constructing and operating blue-green infrastructure to enhance groundwater recharge and mitigate flooding.

Rainwater Reuse and Infiltration:

Sponge cities aim to capture, store, and reuse rainwater effectively. Similarly, MAURICE promotes rainwater reuse in Novy Bydzov to reduce drinking water consumption and rainwater runoff, addressing water scarcity caused by urban sealing and reduced precipitation.

Managed Aquifer Recharge (MAR):

The project incorporates MAR techniques, which are integral to sponge city strategies. For instance, in Milan, the heritage irrigation canal network is used to circulate water during autumn and winter, allowing it to infiltrate agricultural fields and recharge underlying aquifers. This transforms the region into a sponge that absorbs and retains water, reducing evaporation and improving soil conditions.

Urban Drainage and Resilient Design:

Sponge cities focus on enhancing urban drainage systems to manage stormwater effectively. In Ljubljana, MAURICE develops technical design solutions for resilient urban drainage systems to improve stormwater management and groundwater quality.

Monitoring and Data/Model-Driven Adaptation:

The MAURICE project employs advanced monitoring systems and data-driven approaches to evaluate the effectiveness of sponge city-inspired measures. For example, pilots in Stuttgart and Varaždin use comprehensive measurement networks to assess various hydrological parameters enabling prognostic modeling for various climate and groundwater quality and quantity management scenarios.

By integrating sponge city principles into its action plans, the MAURICE project demonstrates how urban areas can adopt innovative water management strategies to enhance resilience to climate change impacts. This approach not only addresses immediate water-related challenges but also contributes to long-term sustainability and ecological balance.

2. Guidance and tools for implementation – overview

It is the objective of the MAURICE to develop proactive measures aligned with ongoing spatial development priorities and emerging regulatory frameworks in the water and planning sectors. Climate-ADAPT, the European Climate Change Adaptation Platform, serves as a comprehensive knowledge hub supporting the EU Mission on Adaptation to Climate Change. It provides up-to-date information on climate trends, adaptation policies, case studies, and practical adaptation measures. Within this framework, the Urban Adaptation Support Tool (UAST) has been developed to support cities, towns, and local authorities in the preparation, implementation, and monitoring of climate adaptation plans.

The MAURICE project followed this structured process based on the Urban Adaptation Support Tool (UAST) recommendations from the European Climate Change Adaptation Platform. This facilitates transition from strategic planning to actionable implementation of climate adaptation measures for urban water management. The MAURICE strategy based on the ADAPT tool has a particular focus on the methodologies applied and lessons learned within the MAURICE project.

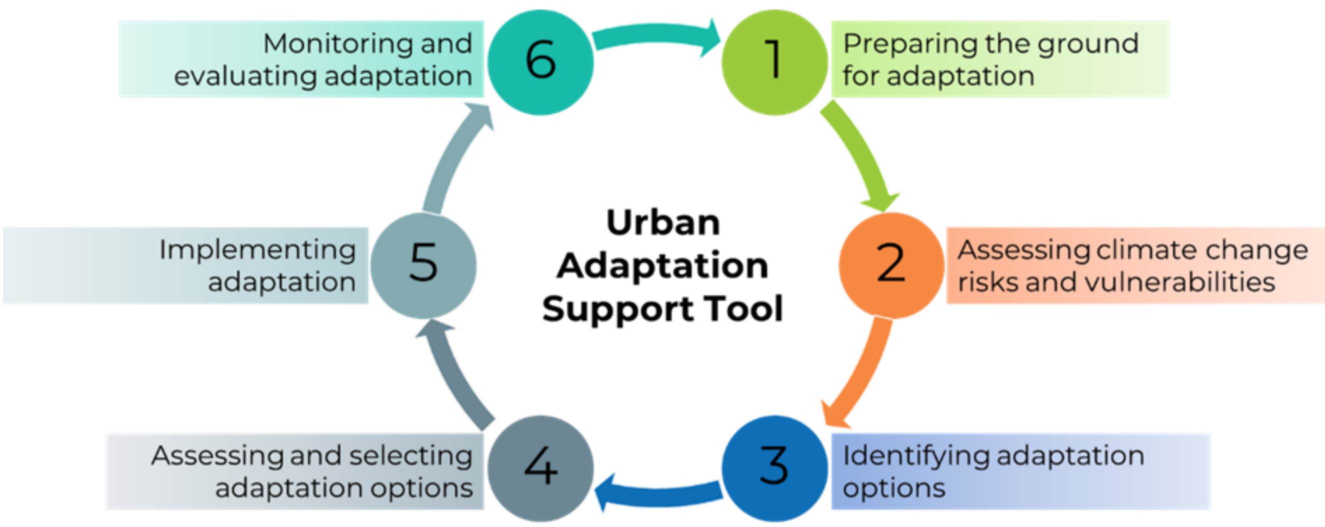


Figure 2-1: Urban Adaptation Support Tool (https://climate-adapt.eea.europa.eu/en/metadata/tools/urban-adaptation-support-tool).

Key steps:

1. **Define Core Questions:**
   Identify climate challenges and goals, secure political support, form a core team, review legal obligations, collect initial data, and engage stakeholders.
2. **Assess Risks and Vulnerabilities:**
   Develop a conceptual model, conduct investigations and pilot actions, and update models for decision-making.
3. **Identify Adaptation Options:**
   Develop locally applicable adaptation options.
4. **Assess and Select Options:**
   Simulate scenarios, set assessment criteria (cost, urgency, socio-economic, environmental), and prioritize options.
5. **Develop and Implement Action Plans:**
   Create detailed plans (measures, roles, timelines, finances, monitoring), involve stakeholders, and secure funding.
6. **Monitoring and Evaluation:**
   Set targets and KPIs, establish monitoring and evaluation, and refine strategies based on results.

MAURICE Tools and Solutions provide methodology and guidance for the key aspects of developing climate resilient sponge cities:

1. Groundwater behaviour forecast as decision support
2. Managing aquifer recharge -ensuring groundwater availability and climate change resilience by adaptation measures
3. Infiltration capacity map –basis for urban planning and decision making
4. Surveying urban water mass flows and contaminant loads to set resilient drainage and infiltration targets
5. Selection of rainwater treatment technologies for further use
6. Implementing rainwater management in cities -Guideline for public administration
7. Designing blue-green infrastructure for rainwater retention and groundwater recharge

The following chapter 3 is structured according to this sequence above of these tools and solutions.

The MAURICE approach connects these elements of strategy and solutions with their implementation in local pilot actions and the development of specific action plans for cities involved. This clearly demonstrates the handling of the elements of the approach and provides illustrative best practise examples.

Figure 2-2: The MAURICE Approach

3. Seven Solutions facilitating the implementation of sponge city concepts

This chapter is structured along the seven formal project outputs "solutions" and highlights key aspects of the solutions and their implementation. For all of them much more detailed information is included in the separate project outputs and related deliverables.

As an example, a wealth of theoretical background and practical aspects around underground infiltration capacity mapping is dealt with in detail in D 4.4.1 – Use of the infiltration capacity map (from field investigation to planning, consenting and decision-making), Interreg CENTRAL EUROPE, 2026.

3.1. Tools for groundwater behavior forecast as support for public authorities' decision making

3.1.1. Introduction

Groundwater behaviour forecast is prerequisite for the development of any CC resilience strategies and measures. Models built on the knowledge and meteorological data acquired of the past decades provide the basis to be combined with various CC scenarios to outline a framework of future situations to be expected. Over the last 70 years, droughts have become more frequent, more intense, and more extensive in Europe (Biella et al., 2025).

In 2022, Milan and its surrounding region experienced severe conditions due to a historic drought that triggered water insecurity and caused major damage to agricultural production. Preparing for such events is essential, as future climate scenarios do not rule out the recurrence of similar crises. The 2022 drought itself had not been anticipated.

In Stuttgart, it is not such an extreme situation as described for Milan, but hydrogeologists are observing a clear trend of falling groundwater levels at parts of the city. Building damages caused by land subsidence have been observed as well as long-term running mitigation schemes for groundwater pollution need to be stopped or modified significantly.

The teams jointly compiled a report covering the practices used to obtain scenarios of climate and other relevant variables under climate change conditions in the two Pilot Actions Stuttgart and Milan. The methodology utilized in the two areas is explained and the results are presented. The result of the work presented here is of crucial importance for all further action planning.

3.1.2. Methodology

The Stuttgart team choose a traditional hydrological modelling approach relying on a physically based model fed with future climate scenarios. Considerations on future climate change scenarios are based on the 5th IPCC (Intergovernmental Panel on Climate Change) assessment report. It presents future climate scenarios as “representative concentration pathways” (RCPs). The numbers in the RCP’s names refer to radiative forcing, measured in watt per square meter. Four “representative” scenarios (Representative Concentration Pathways RCPs) were selected, describing possible climate futures based on radiative forcing values, measured in watt per square meter (W/m2), by the year 2100 (Figure 3.1.2-1).

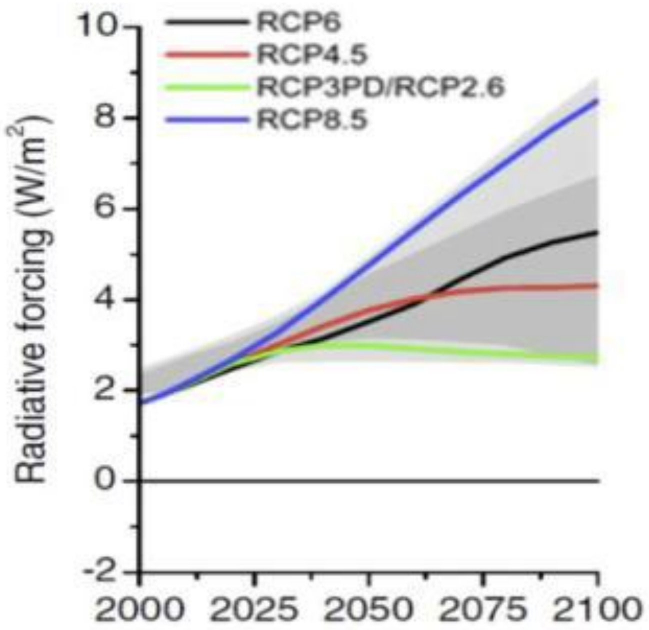


Figure 3.1.2-1: Representative Concentration Pathways

The most consolidated method to assess the impacts of changing drivers on water resources systems is through the downscaling of global scenarios to the local scale. The Top-Down strategy involves a downscaling of the climate variables from Global Climate Models (GCMs), under a range of possible emissions scenarios, to the local scale through the Regional Climate Models (RCMs).

A set of techniques is available to downscale the global models’ variables to higher resolution. Particularly used for their accuracy and availability of variables are the products obtained from EURO-CORDEX (Coordinated downscaling experiment - European Domain).

They refine the results of the Global Climate Models using various methods for higher resolutions (grid size ~2 to 5 km) no longer for the entire earth, but for smaller regions, such as southern Germany. CORDEX Data are bias-corrected and made available by the German National Climate Agency (Deutscher Wetterdienst DWD).

With regard to global climate modeling, a next generation of models has been available since 2021 with the 6th IPCC Assessment Report. However, no reliable results are yet available for the regional area.

The federal states Baden-Württemberg, Bavaria and Rheinland-Pfalz in Southern Germany joined forces in the KLIWA cooperation, to determine and evaluate the future effects of climate change. One result of this cooperation is the predicted impact of climate change on the soil water balance and groundwater recharge.

KLIWA uses the worst case (RCP8.5) with the highest assumed amount of greenhouse gas emissions. It corresponds to a world in which no climate protection measures are taken. Nine projections based on dynamic climate models have proven to be suitable for southern Germany. In the groundwater sector, the

KLIWA ensemble is supplemented by four statistical climate projections. They are the basis for current water balance modelling.

In Milan the simulation of the aquifer and the irrigation system dynamics in the area under study requires knowledge of the meteorological and climate context as well as the surrounding conditions, specifically the flow rates taken at the Panperduto dam toward the Villoresi Canal, and the flow rates passing downstream of the same dam towards the Ticino. The average daily values of these flow rates have been known since the construction of the Miorina dam, regulating the Lake Maggiore and was built in the 1940s. This dam modulates the flow rates entering the Panperduto node, and it is therefore crucial to consider its behaviour within the proposed model.

The study does not limit itself to reconstructing what happened historically but aims to provide elements to estimate what the effects could be in the future, considering the current climate evolution. It is therefore necessary to identify relationships that allow estimating the previously mentioned flows, starting from the formation of the inflow to Lake Maggiore, which collects the waters that fall on a catchment area of about 6600 km2, partly in Italy and partly in Switzerland.

The team decided to use a pair of cascade models: the first, to estimate the values of the inflow to Lake Maggiore starting from temperature and precipitation data, representative of the conditions of the catchment area; the second, to obtain the two flows of interest starting from the inflow estimated by the first. These models, once identified, were fed with the projections of the climatic variables obtained as described in Deliverable 1.3.1 to which reference is made.

From a methodological point of view, the models were designed using machine learning techniques and recurrent neural networks (RNN) and Long Short-Term Memory (LSTM). Traditionally, hydrological modelling has relied on physically based models, which represent hydrological processes through differential equations derived from physical laws. Although these models provide a deep understanding of the underlying mechanisms, their application can be challenging due to the large number of parameters to be calibrated, their dependence on the availability of detailed physical data, and their difficulty in capturing the extreme nonlinearity and spatial and temporal variability of hydrological systems (Beven & Freer, 2001).

Unlike physically based models, RNNs and LSTMs are data-driven models, meaning they learn input-output relationships directly from observed historical data. Their inherently recurrent architecture makes them particularly well suited to modelling time series, such as those typical of hydrological data.

LSTMs are emerging as promising tools for hydrological simulations such as river flow forecasting, runoff simulation, evapotranspiration estimation, and other applications (Kratzert et al., 2018; Hu et al., 2019; Hunt et al., 2022; Liu et al., 2024; Hosseini et al., 2024). Recent papers highlight how the use of LSTM networks has improved water flow forecasts in complex basins, highlighting the ability to capture nonlinear temporal dynamics (Zhang et al., 2022). In cases of poorly structured data, it has been shown (Li et al., 2023) how deep learning models, including recurrent ones, are more effective than traditional methods, feeding more reliable forecast scenarios. Innovative techniques have also been proposed to improve the performance of these models to accurately reproduce flood peaks (Martel et al., 2024a).

In summary, the choice of model depends on the specific goals of the simulation, the availability of the data, and the level of interpretability required. The comparison between data-driven models (such as RNN/LSTM) and physically based models is an active research topic (see e.g. Lei et al., 2023; Fuente et al., 2024; Martel et al., 2024b). While physically based models offer greater interpretability and can be generalized to unobserved scenarios (if the physical processes are well understood and represented), they require in-depth knowledge of the system and can be computationally expensive. In contrast, LSTM models excel at prediction based on historical data, are faster to run once trained, and can capture complex relationships that would be difficult to express in physical equations. However, their “black-box” nature can make it difficult to interpret the “why” of a specific prediction, and their performance is highly dependent on the quality and quantity of the training data.

3.1.3. Results Stuttgart

Key drivers from a water budget perspective are past and future evolution of air temperature and precipitation. Air temperature has a significant influence on evaporation and thus also on precipitation. The warmer the air mass, the more water it can absorb. This increases the maximum possible amount of precipitation. On the other hand, rising air temperature leads to longer vegetation periods, thus increasing evaporation, leading to a lower seepage water rate and consequent decrease in groundwater recharge.

Analysing the past evolution already shows distinctly rising temperatures since 1990 with a further intensifying trend after 2000. According to KLIWA climate projections for southern Germany (worst case scenario RCP8.5), temperature can increase by an average of 3 to 4.4°C until 2100 compared to the timeline 1971-2000.

The amount of precipitation and its temporal variability have a central effect on all other variables in the water balance. The trend towards more frequent and more intense heavy precipitation events increases the proportion of rapid lateral runoff components and thus simultaneously reduces infiltration and groundwater recharge. On the other hand, European cities increasingly strive for implementing sponge city concepts, with a perspective for mitigation in the long term.

Analysing the past evolution already shows a distinctly decreasing tendency with hardly any years above average (green line) after 2003. See following Figure 3.1.3-.

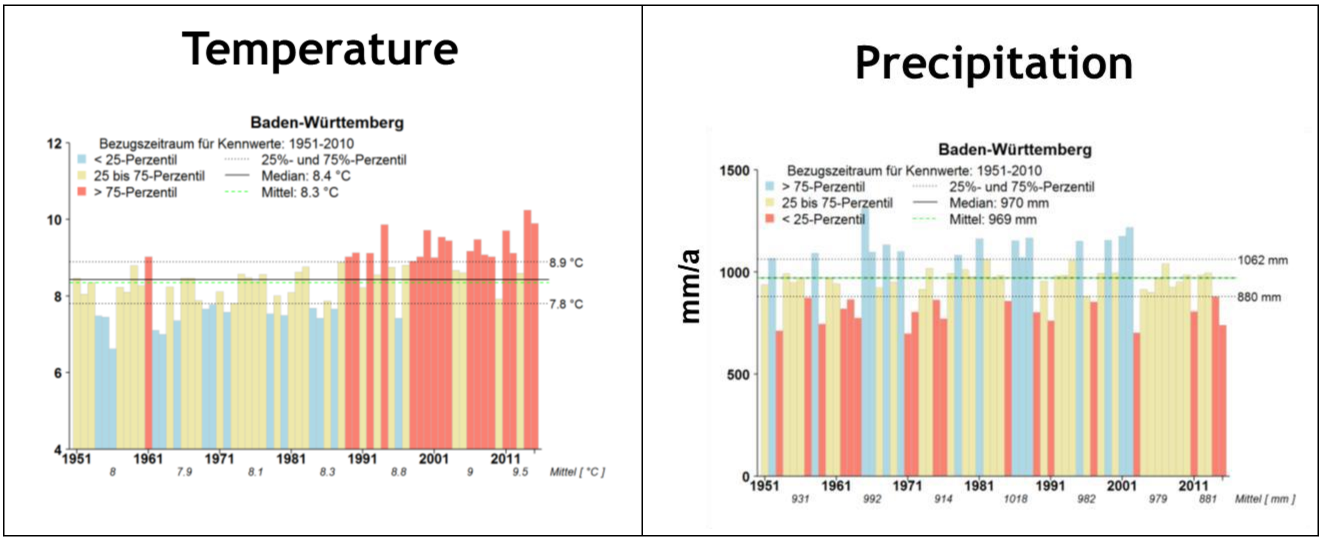


Figure 3.1.3-1: Evolution of air temperature and precipitation in Baden-Württemberg since 1951

Groundwater recharge represents the balance of precipitation minus evaporation and surface runoff. As a “balance residual”, it therefore reacts particularly sensitively to changes in the climate and decreases in precipitation.

Scenario simulations based on the KLIWA ensemble were carried out to investigate the question of future changes in groundwater recharge due to climate change. A soil water balance model was established to determine long term mean groundwater recharge rates on the basis of measured values. WETTREG is a statistical regionalization procedure that generates results (realizations) on the basis of station data for those stations where measurement series are available.

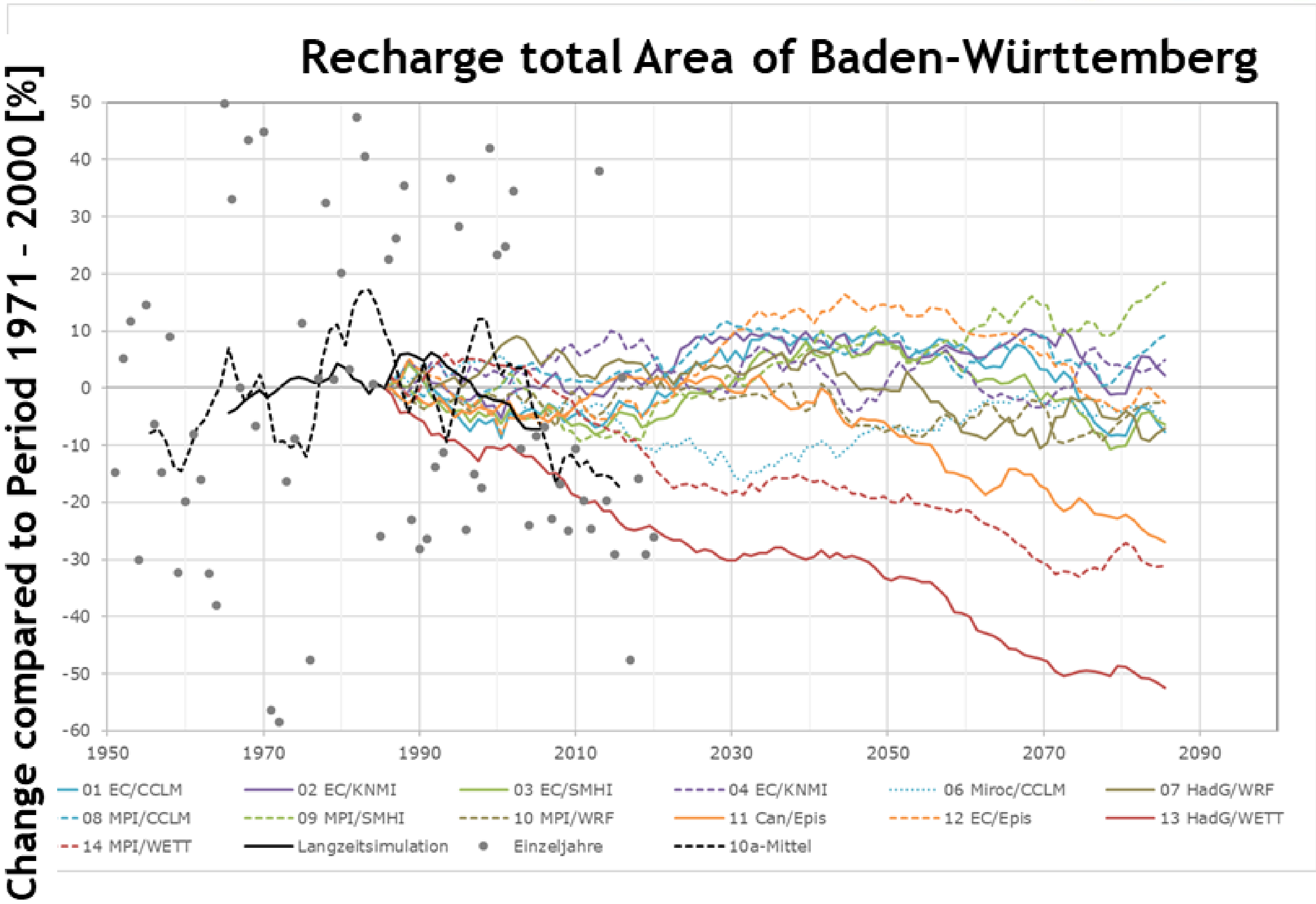


Figure 3.1.3-2: Long-term simulation to illustrate the high annual variability of groundwater recharge from precipitation

Figure 3.1.3-2 – 30-year moving average of the relative change to the reference period 1971-2000 of past (black line, long-term simulation based on measured data) and projected groundwater recharge of the various projections of the KLIWA ensemble, for state Baden-Württemberg. Grey dots show the individual annual mean values from the long-term simulation to illustrate the high annual variability of groundwater recharge from precipitation.

The WETTREG forecast for groundwater recharge in Figure 3.1.3-3 shows the long term past evolution in combination with 13 selected future projections. They were selected by KLIWA on basis of an audit process. They are all based on the RCP 8.5 (worst case) scenario with the aim of providing a good reflection of the range of possible developments in soil water balance dynamics.

According to the past long-term simulation a deficit in groundwater recharge has built up since 2003. Combining soil water balance simulations, based on measured data, with climate projections, it becomes clear that the development of groundwater recharge in recent years is currently tending towards the dry, lower edge of the extended KLIWA ensemble.

Figure 3.1.3-3 shows the regional distribution of expected groundwater recharge reductions in the state of Baden-Württemberg for the years 2036-2065 compared to 1991-2020. For the Stuttgart region, a decrease of 25% is expected.

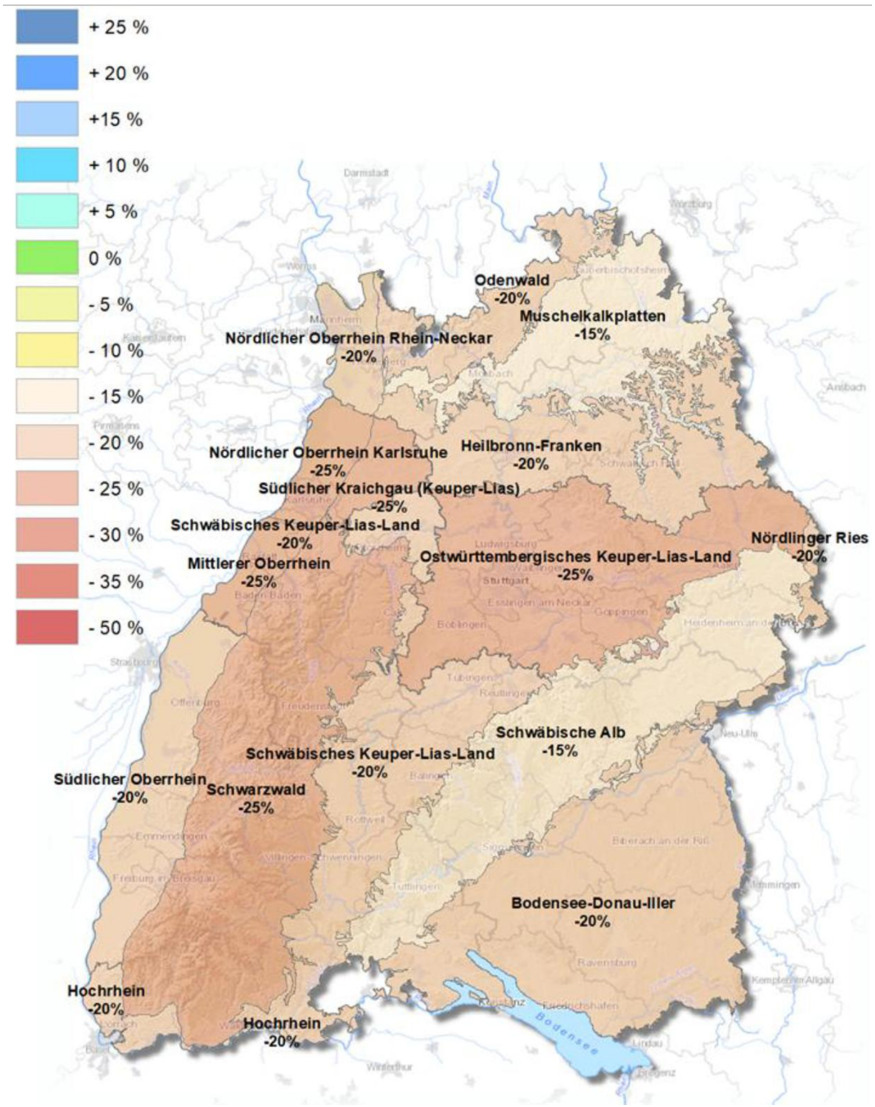


Figure 3.1.3-3: Expected Regional Distribution of Groundwater Recharge Reductions in Baden-Württemberg for the years 2036-2065 compared to 1991-2020, according to KLIWA worst case scenario

For the project area in Stuttgart – Feuerbach the water balance was calculated using a soil water balance model and a hydrological model. The northern part of the project area (mainly urban area of Feuerbach) was simulated with a soil water balance model (GWN-BW, GIT HydroS Consult GmbH, 2014), used to estimate grounwater recharge and evaporation rates, since no relevant surface runoff could be expected. For a hydrological assessment of the southern project area, where surface runoff had to be included, the soil another hydrological model was developed using the HecHMS 4.11 software (U.S. Army Corps of Engineers, 2023) within the extents of the southern Feuerbach basin.

These calculations reveal, that since 2000 the ten years moving average shows a decrease of approximately 20%.

Scenario calculations for future development were based on WETTREC prognosis. Corresponding with our project area past evolution we decided to choose the worst case-scenario (13 HadG/WETT) with a decrease of groundwater recharge of around 25% in the period 2036-2065 (compared to the period 1990-2020). Figure 3.1.3-4 shows an extrapolation from past evolution to future development based on this scenario 13. We used this assumed evolution as input parameter for scenario calculations in the groundwater model.

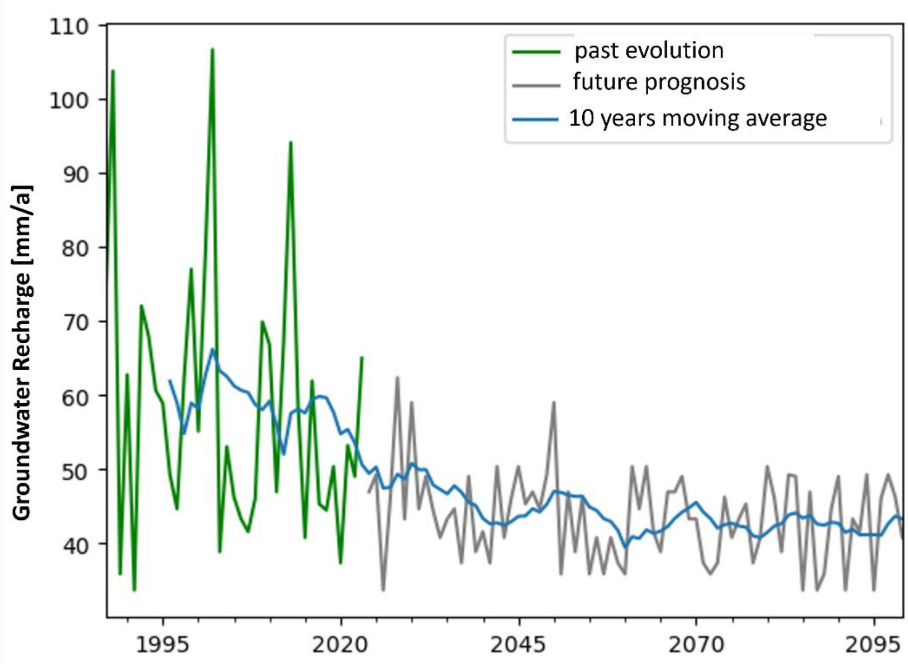


Figure 3.1.3-4: Past evolution and assumed future development of groundwater recharge according to WETTREC scenario 13 with past development (green line), future prognosis (grey line) and moving average over 10 years (blue line).

3.1.4. Results Milan

According to the sophisticated modelling approach chosen by the Milan team, tremendous efforts on statistical processing and analysis were required. Reliable time series of the climatic variables were needed to feed the models described previously. Both to simulate the Lake Maggiore upstream system, and those used to feed the model of the valley irrigation downstream system for the case study area. In both cases, the EURO-CORDEX dataset was used, in particular the projections provided by the Aladin, RegCM4 and RACMO models in correspondence with the RCP8.5 scenario. For the methodological description of the techniques used and for the related bibliographic references, see D1.3.1.

Climate variables

For the upstream system precipitation and temperature time series were obtained for the stations of Domodossola and Crodo, in Italy, and Lugano, Locarno and Magadino, in Switzerland, considered overall representative of the catchment area of Lake Maggiore. As a final result Figure 3.1.4-1 shows the annual values [mm/year] before and after downscaling until 2050.

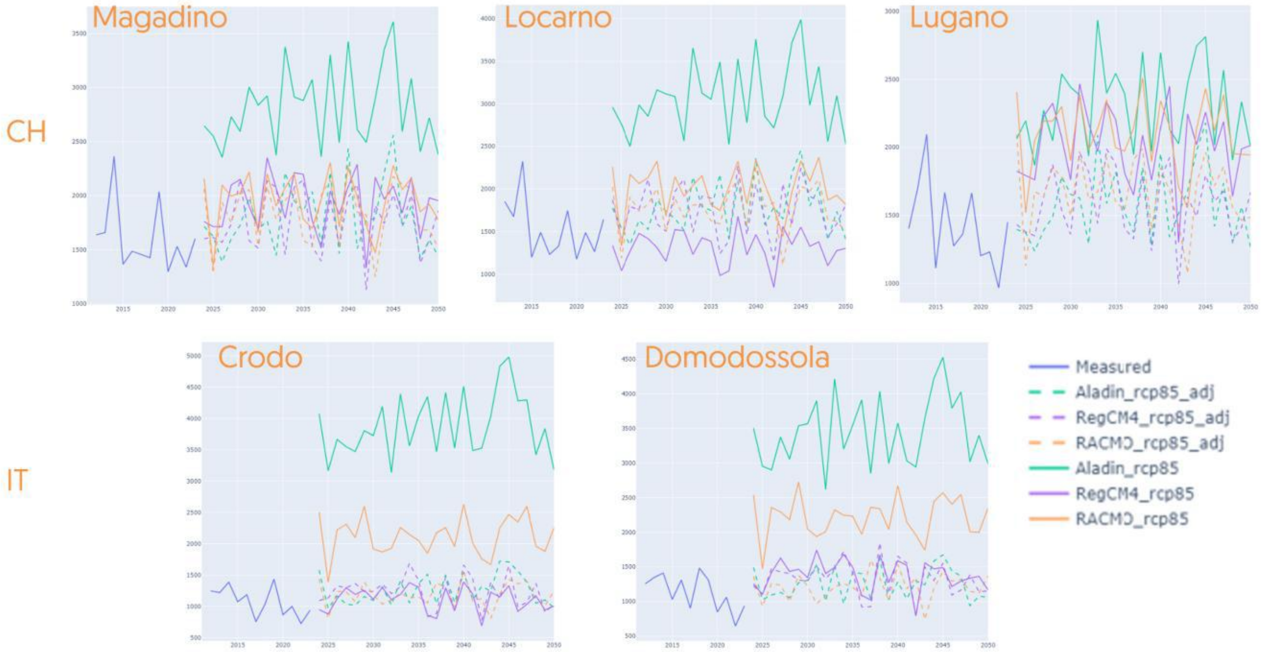


Figure 3.1.4-1: Yearly total precipitation in the future horizon for all downstream used stations corresponding to each of the models used, before and after the downscaling operation with the LOCI + EQM methods compared with the measured values.

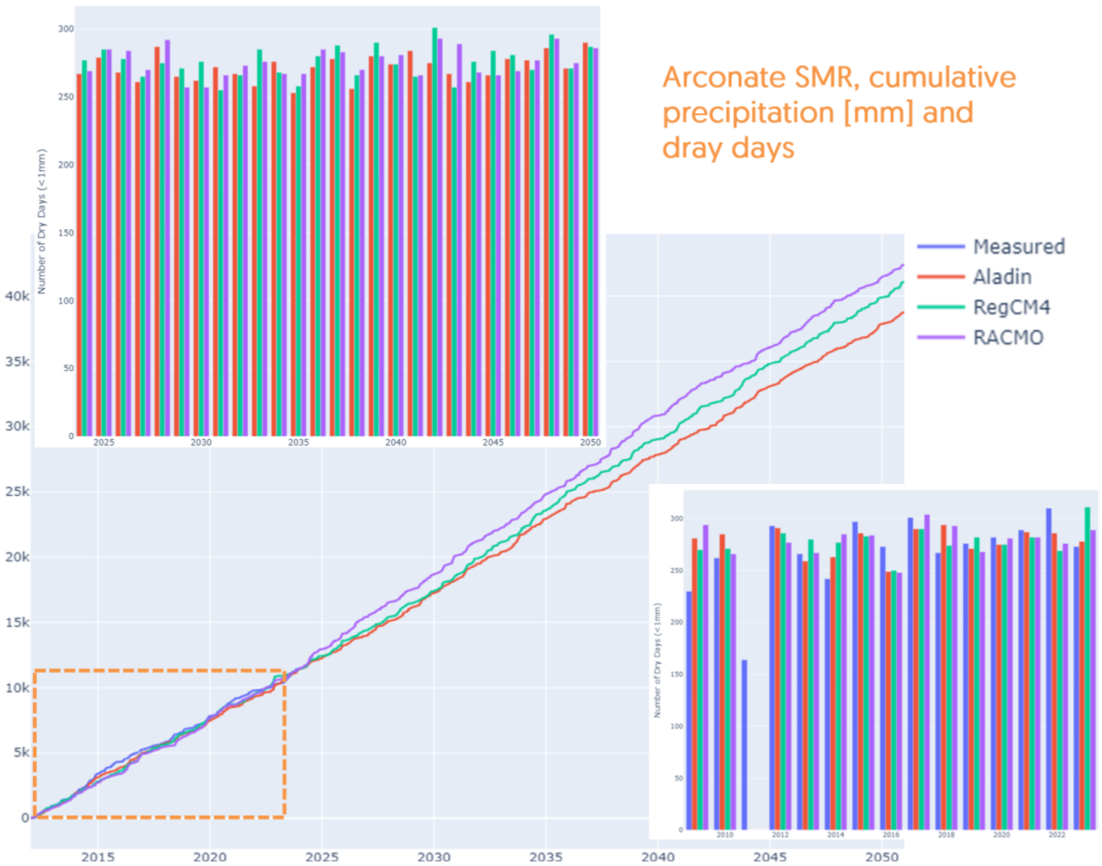


Figure 3.1.4-2: An example of the cumulative daily precipitation in the future horizon (main plot), comparison of number of dry days in the control period (small plot on the bottom-right) and in the future horizon (small plot on the top-left side) corresponding to each of the models used, after the downscaling operation with the LOCI + EQM methods

In the downstream system the valley irrigation system model requires the production of time series for 7 variables (minimum and maximum temperature and humidity, precipitation, irradiance and wind speed) for 7 stations (Landriano Cascina Marianna, Cinisello Balsamo Parco Nord, Arconate SMR, Corsico v.le Italia, Rescaldina, Pogliano Milanese, Rho Scalo Fiorenza – Prato).

To produce the precipitation time series, the same method described previously was adopted, utilizing the LOCI + EQM pipeline in order to adjust the frequency of days with no rain between projections and ground measurements. The synoptic result containing also the trend of the cumulative precipitation for a station and for the 3 models is shown in Figure X.

Surface water flows

The time-series described above were used to feed the rainfall-discharge model, implemented with the LSTM architecture introduced in the methodological part. For greater control of the results, the discharges estimated by this model were compared with those produced by a physically based model with lumped parameters, HBV, appropriately calibrated by coupling it to a state-of-the-art genetic optimization engine.

The comparison for the Lake Maggiore inflow shown in Figure 3.1.4-3 is merciless, by looking at both the cumulative and annual volumes, the underestimation produced by HBV is decidedly high. On the contrary, LSTM provides acceptable values, more than satisfactory considering the objective of the work.

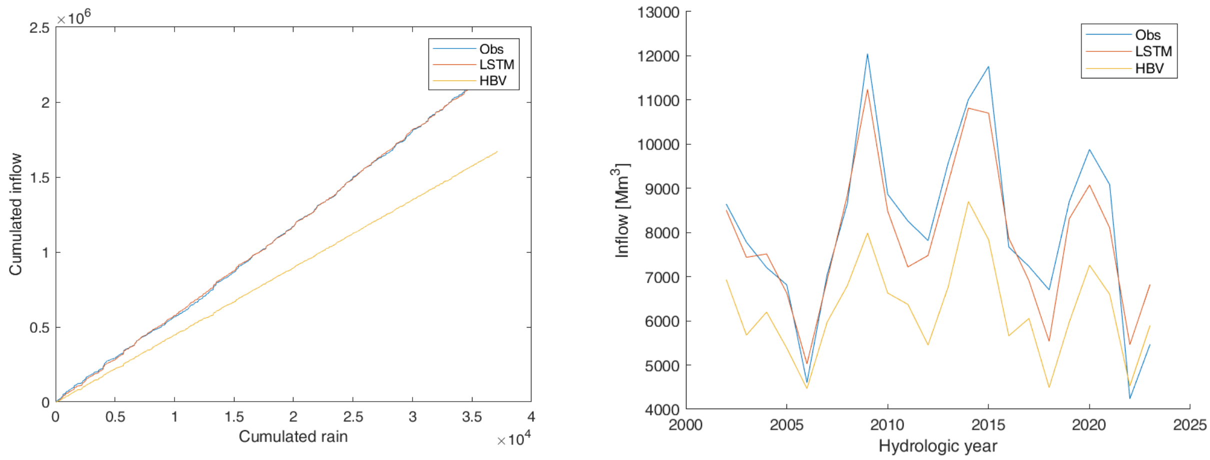


Figure 3.1.4-3 - Comparison between observed inflow (obtained by daily water balance), and LSTM and HBV estimations, considering their cumulative values respect the cumulative precipitation (on the left) and the yearly volume (on the right).

Overall, the daily averages obtained considering the same ten-year intervals used to describe the inputs (always corresponding to the RegCM4 model), are shown in Figure 3.1.4-4. Moving from the past decades to the most recent ones and those more distant in the future, a significant reduction in high flows is expected, both due to the disappearance of part of the contributions deriving from the melting of the glaciers, and due to a reduction in the intensity of autumn rains. At the same time, a shift between one to two months in local maximums is observed, especially those usually observed in spring, and those in autumn. A third local maximum also appears to be consolidating, corresponding to the late summer period.

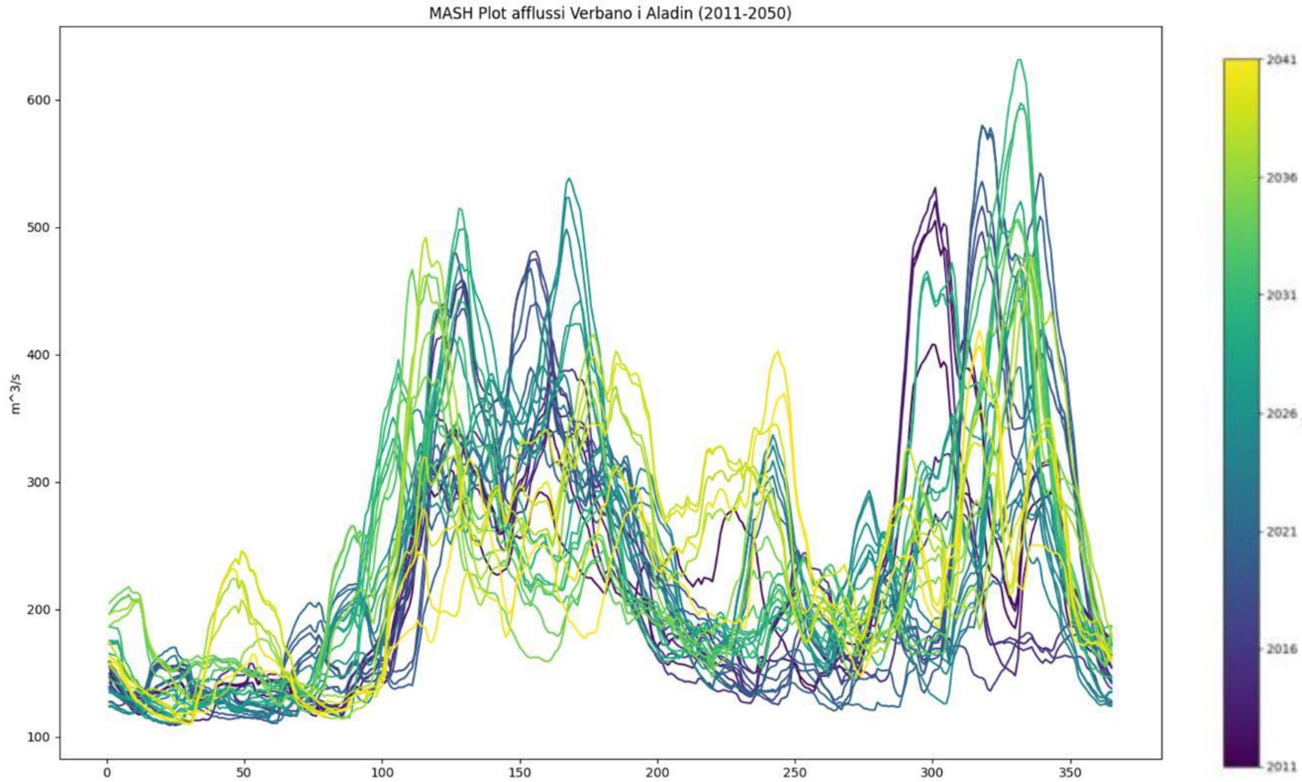


Figure 3.1.4-4: The moving daily cyclostationary average considering ten-year intervals of the LSTM estimated inflow considering Aladin inputs.

The outputs of the previous model represent the inputs to simulate both the dynamics of Lake Maggiore and the regulation operations of the Miorina dam and the Panperduto dam to obtain the derived flow in the Villoresi canal and the residual flow in Ticino river.

The comparison of the monthly averages of the Villoresi flows, obtained in the control period in which the measured data are available, highlights an excellent adaptation of the model (left graph of Figure 3.1.4-5), demonstrating the reliability of the projections up to 2050, always represented at monthly frequency, in the right graph.

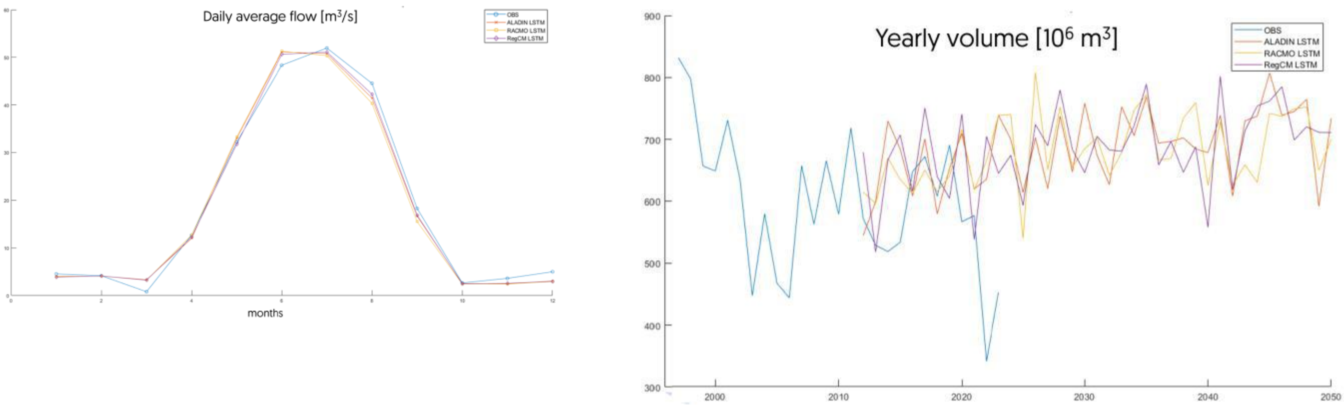


Figure 3.1.4-5: The overall monthly average (on the left) and the yearly volume (on the right) of the LSTM estimated Villoresi flow downstream Panperduto dam corresponding to each of the models used.

Overall, the daily average calculated on the usual ten-year intervals up to 2050, highlights the tendency to flatten the curve, not allowing the same maximum values historically measured to be reached (reduction of 4 to 5 m3/s), but at the same time managing to support the diversions even in the final part of the irrigation season.

The residual flows in Ticino are characterized by a much higher variability, and the model unfortunately underestimates systematically the flood peaks recorded historically. However, there is a good match the behaviour in correspondence with the low and medium flows, considering the purpose of the project. The results are shown by the daily average calculated on the ten-year intervals up to 2050 reported in the Figure 3.1.4-5. The pattern in this case is less recognizable, from one decade to another there can also be very significant deviations. However, it seems evident that a significant flattening of the flow rates seems to reflect the trend of the inflows to the lake as described above.

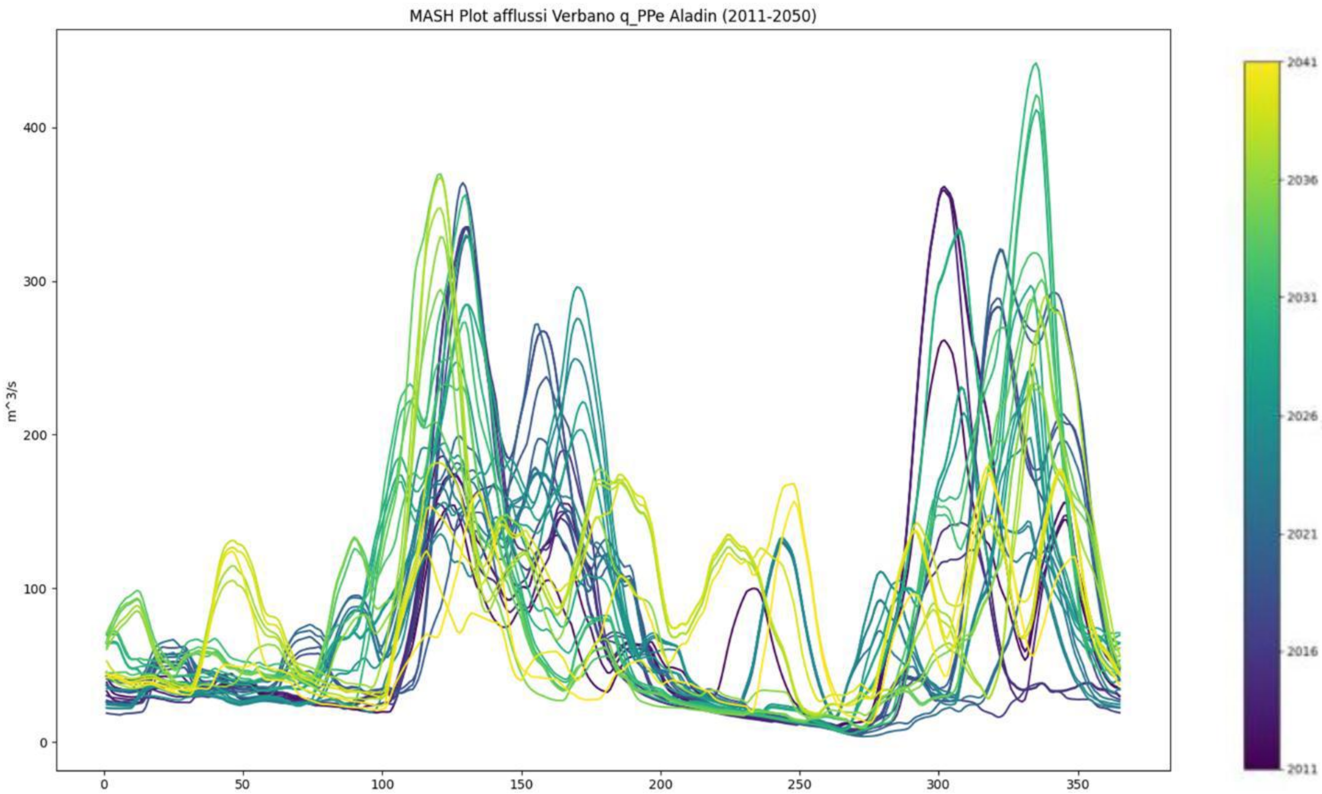


Figure 3.1.4-6: Moving daily cyclostationary average considering ten-year intervals of the LSTM estimated Ticino flow downstream PanPerduto dam considering Aladin inputs.

3.2. Guideline to ensure groundwater availability and climate change resilience by adaptation measures

3.2.1. Introduction

Different lines of action can be pursued to enhance urban water management, as demonstrated by the outcomes of the MAURICE project and synthesised in the holistic “Sponge city” approach. Nevertheless, following the Climate-ADAPT’s framework for adaptation to climate change, priorities should be defined based on the specific climate risks and vulnerabilities of each urban area, and actions should be tailored to the local social, economic, and environmental context. The pilot actions in Milan and Stuttgart focused on managing aquifer recharge, governing groundwater quantity management in metropolitan settings.

The document presents:

- A framework to assess urban adaptation solutions enabling aquifer recharge, based on the case of the City of Stuttgart-Feuerbach;
- Guidelines for the implementation of Agricultural Managed Aquifer Recharge, based on lessons learned from the pilot action in the metropolitan area of Milan.

Stuttgart-Feuerbach represents an urban area that is affected by a dramatic decline in groundwater levels during the last 10-15 years. Due to a very complex geology with varying hydrogeologic properties, mitigation measures need careful planning. In the planning process different urban adaptation options aimed at enhancing aquifer recharge were evaluated. This relied on long-term groundwater monitoring data, field test data, and results from a numerical groundwater model for the pilot area, developed to understand the system’s behaviour. With the model scenario simulations were performed to assess the effects of possible adaptation options on the groundwater levels.

Milan pilot action focuses instead on an agricultural area within the metropolitan area, where future climate conditions may reduce water availability during the irrigation season. Leveraging the presence of a dense irrigation network, a tailored adaptation measure was developed and tested over three consecutive winters: water was circulated through irrigation canals during winter and subsequently distributed across agricultural fields to promote infiltration and recharge the aquifer below. lessons learned throughout the implementation of this pilot action provide guidance for the implementation of Agricultural Managed Aquifer Recharge as a drought-adaptation measure”.

3.2.2. Urban adaptation solutions enabling aquifer recharge

By a first qualitative assessment of potential adaptation measures the following 4 categories proved to be widely applicable in urbanized settings:

1. Unsealing of selected areas:

   Extensive sealing (in Stuttgart-Feuerbach more than 70 % of the surface is sealed) increases surface runoff and limits infiltration and groundwater recharge. By using existing gaps or by redeveloping areas after demolition of buildings, small spaces of blue-green infrastructure could be implemented, enhancing not only groundwater recharge but also increasing the overall quality of living. In addition, remodeling parking areas by installing semi-permeable surfaces, such as grass paving blocks, can contribute to higher infiltration rates and support the restoration of groundwater levels.

2. Targeted Infiltration of Roof Water and Surface Runoff:

   In the context of site development facilities to collect roof water and road runoff can be integrated with targeted infiltration systems, such as infiltration ditches or drain trenches. This requires prior assessment of the sites' infiltration capacities, as the permeability of soil strata varies considerably across the district. However, even small infiltration volumes can improve moisture of soil, support vegetation growth, thus improving urban climatic conditions.

3. Construction and Operation of Infiltration Wells

   The construction of infiltration wells in permeable subsurface layers with a higher intake capacity, enables efficient input of water into the aquifer. In contrast to infiltration by trenches, these systems can convey significant larger volumes directly to deeper, more permeable layers, efficiently recharging groundwater resources. Carefully planned, the risk of flooding basements can be avoided. However, considerable amounts of water need to be available locally.

4. Reduction of Groundwater Extractions

   With the decline of groundwater levels in the Feuerbach area during the last decades, the amount of water extracted by wells also went down dramatically. Since 2010, extraction rates declined from approximately 8 l/s to approximately 2,5 l/s. Figure 1 gives an impression. Further water losses can be avoided, e.g. by preventing groundwater drawdowns for building construction by appropriate measures or by re-infiltration. Any discharge of fresh water to sewage should be avoided in any case.

To identify the most effective adaptation option, an assessment of their quantitative influence on the overall groundwater resources is required. For this purpose, the use of decision-support tools is recommended. This was done for the Stuttgart-Feuerbach area based on a numerical groundwater flow model established during the MAURICE project.

Using this model, the possible effects of the first three adaptation solutions described above were analysed and assessed against future climate projections. Regional climate prognosis models for the upcoming period 2036–2065 indicate that groundwater recharge in the area is estimated to decline by 25% to 50%, compared to the period 1991–2020. This translates into an additional input required by the aquifer between 12 and 20 l/s, necessary to compensate for this deficit and reverse the current trend of sinking groundwater levels.

Increase of Groundwater Recharge by unsealing measures in Stuttgart-Feuerbach has been estimated at 200 mm/y. This corresponds to a recharge rate of 6.3 l/s per km². Each additional km² of unsealed surface can therefore generate additional 6.3 l/s of water input, thus providing a significant contribution toward compensating the existing groundwater deficit.

The numerical model was used to test effects of **surface infiltration through infiltration trenches**. In this case, 2.5 l/s of water were continuously infiltrated to the upper quaternary aquifer in the northern part of the district. Figure 3.2.2-1 shows the effects in the aquifer after one year of continuous infiltration.

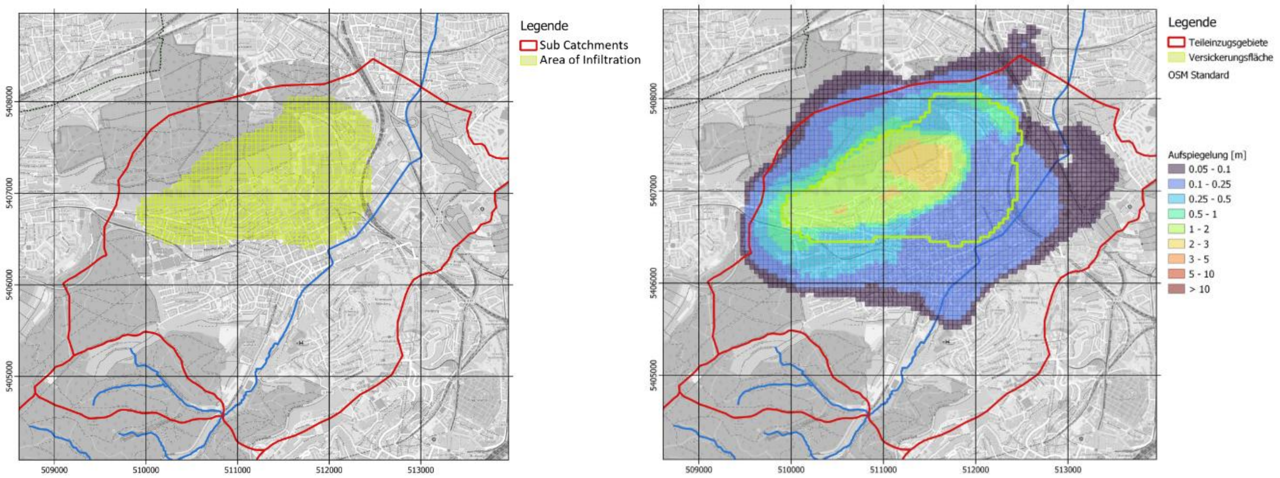
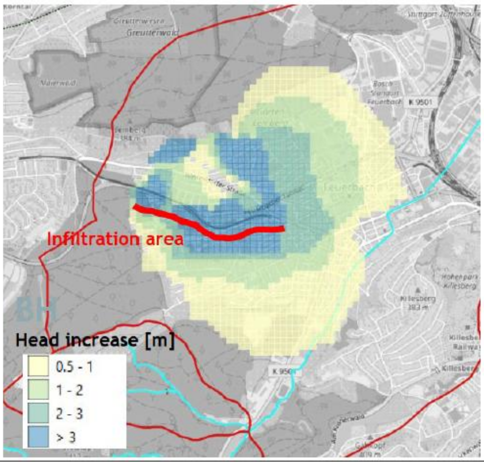


Figure 3.2.2-1: Area of assumed infiltration in the groundwater model and groundwater elevations in quaternary aquifer after one year of infiltration

In a next step Stuttgart team examined the effects of a targeted infiltration via wells, tapped in selected aquifers and in different parts of the Feuerbach. Local well infiltration was simulated for different layers of the shallow aquifer system. Infiltration runs were implemented: in the western part of the central city district, west of city center, south of city center, near Feuerbach creek, and in the western periphery.

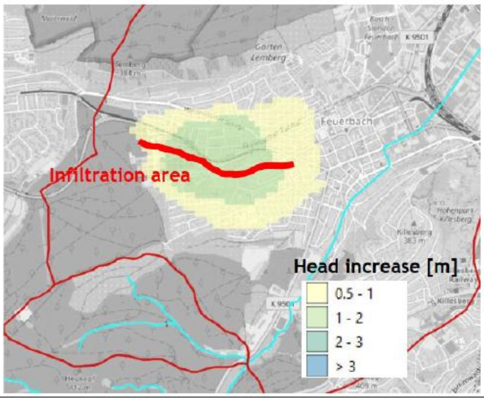
The procedure is demonstrated here by the Infiltration in the central city district. Figure 3.2.2-2 (upper image) shows the effects of infiltration into the aquifer Bochinger Horizont by a row of five wells (red line) along street B 295 with an overall input rate of 10 l/s. The chosen location corresponds with a comparatively high permeability zone within this aquifer. The lower images show effects on the underlying Grundgipsschichten und the uppermost quaternary aquifer.



Infiltration in aquifer Bochinger Horizont

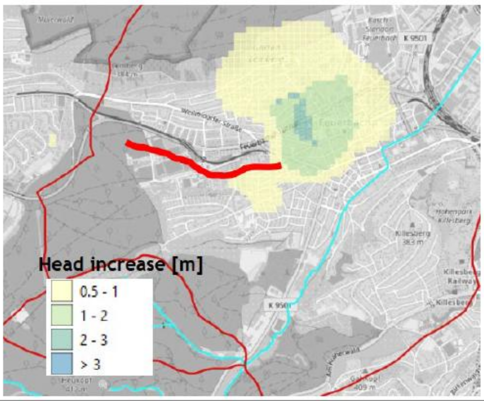
Geohydraulic Reactions in Bochinger Horizont

- Head increase of 0.5m up to a distance of 1 km, including Feuerbach city hall
- Head increase near infiltration area up to 3 m
- Groundwater levels are deeper than 4 m below ground surface.



Quaternary

- Head increase of 0.5 m up to a distance of 0.6 km
- Head increase near infiltration wells up to 1.5 m



Grundgipsschichten

- Head increase of 0.5 m up to a distance of 0.6 km

Figure 3.2.2-2: Distribution of hydraulic levels following an infiltration of 10 l/s into Bochinger Horizont.

This option achieves distinct increases of water levels in the central city area, not only in the infiltration horizon Bochinger Horizont, but also in the shallow quaternary aquifer. However, water levels are still low enough to avoid the risk of flooding basements. In the same way model runs were performed for all other locations mentioned, with varying infiltration rates to different aquifer horizons. This provided decent information about spatial effects which can be achieved and potential risks in low permeability areas.

These results illustrate the use of numerical models as prognosis tools to understand the effects of different adaptation options within a local hydrogeological system. It is essential not only to characterise the area but also to represent the interactions among its components. Numerical models are widely used for this purpose, as they simulate groundwater processes mathematically and allow the testing of scenarios in complex systems, supporting informed groundwater-management decisions.

In MAURICE, climate-change projections were integrated into the assessment framework for evaluating adaptation options. When working with climate data and groundwater models, it is important to consider:

- Climate data are usually available at large-regional scales, whereas groundwater processes are locally shaped by geology and soil conditions. Applying coarse-scale climate data to the fine resolution of a groundwater model introduces statistical uncertainties.
- Climate scenarios exhibit a wide range of variability. While temperature trends show a stable increase, precipitation fluctuates significantly, which complicates the calculation of recharge.

3.2.3. Guidelines for Agricultural Managed Aquifer Recharge

Milan Pilot Action enabled the on-field experimentation of agricultural managed aquifer recharge (Ag-MAR) in a peri-urban setting close to Milan. The area presented many challenges: the coexistence of agricultural and urban areas, the presence of groundwater dependent ecosystems, the relationship between various stakeholders. Since the project included a simulation of future climate and irrigation derivations, a refined methodology had to be followed.

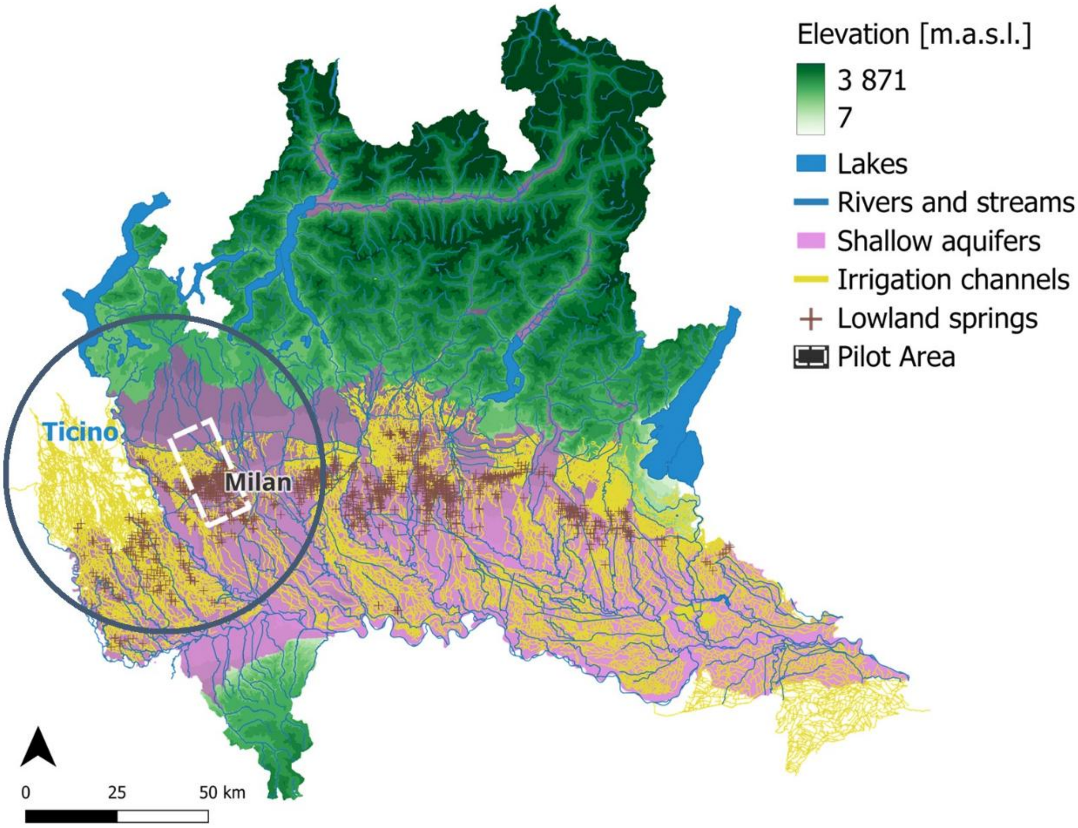


Figure 3.2.3-1: Peri-urban on-field experimentation setting for Ag-MAR near Milan.

The general approach: off-season irrigation used as an additional source of groundwater recharge during periods of low demand. By harnessing the capillary surface-irrigation infrastructure, part of the region's cultural heritage, and the agricultural fields surrounding Milan, it becomes possible to store additional volumes of water in the extensive aquifer system underneath the region. This reserve can then be used during droughts to help alleviate the unmet water demand for irrigation. This solution can also be activated once the drought has ended and the surface water bodies have returned to normal conditions, to accelerate the recovery of groundwater levels.

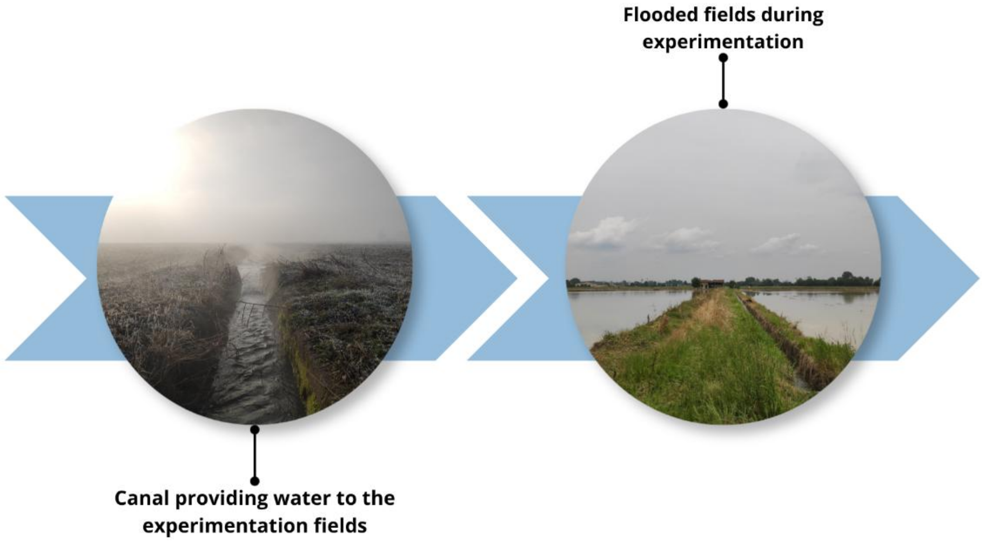


Figure 3.2.3-2: Irrigation canal and flooded fields.

Testing Ag-MAR in Milan

The MAURICE Pilot Action in Milan tested this solution on 33 hectares of pilot fields, in collaboration with the Est Ticino Villoresi irrigation consortium and three farmers. The first step was to collect data to characterize the area. During the winters of 2023-2024 (start of December to end of January) and 2024-2025 (mid-October to end of February), an average of 2.900.000 m3 of water per month was mobilized and infiltrated along the distribution canals and on the fields. Since the fields were not cultivated, the practice is classified as submersion rather than irrigation. A network of manual and automatic groundwater-level monitoring points enabled us to reconstruct the behaviour of the aquifer system during the project and in response to the experimental recharge. This information is crucial for evaluating the outcomes of the tests. We complemented these data with observations of groundwater-dependent ecosystems in the area (i.e., lowland springs, or fontanili in Italian) to obtain a clear picture also of the aquifer outflows, as these features drain the system.

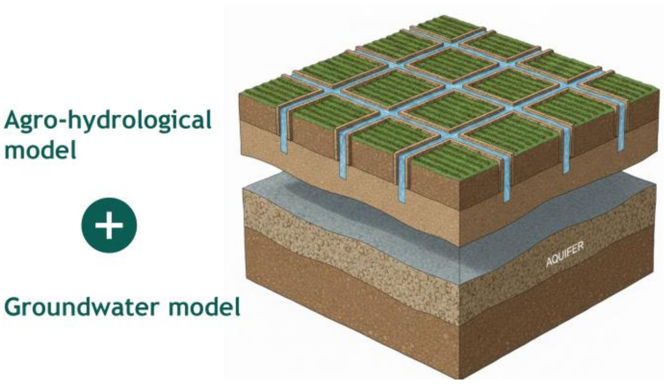


Figure 3.2.3-3: Agro-hydrological and groundwater model.

The data was used to build and calibrate an agro-hydrological model and a groundwater model. By coupling the models, we were able to derive key water-balance information and simulate the system behaviour under different climate and adaptation scenarios.

Results of Ag-MAR implementation in Milan

Field data showed that approximately 6 Mm^3 and 8 Mm^3 of the mobilized water infiltrated during the two test winters.

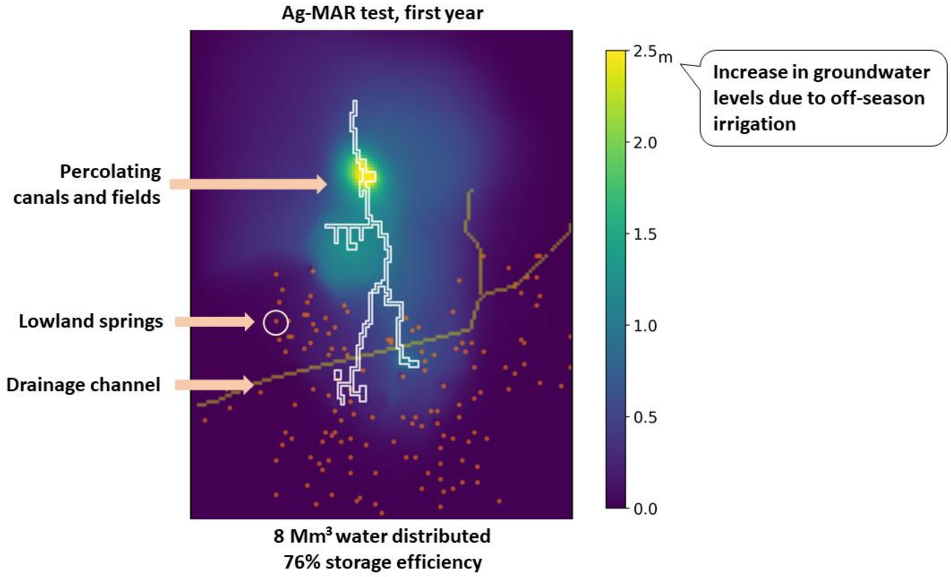


Figure 3.2.3-4: Model results of infiltrated volumes.

Model results indicate that, on average, 68% of the infiltrated volume remained in the aquifer at the end of each implementation period, and 58% was still stored at the beginning of the following summer irrigation season. This means that, even at pilot scale, more than 4.000.000 m^3 of water were effectively stored and could have been used by farmers during a drought. This volume corresponds to about 30% of the water deficit recorded in 2022 over the same area compared with historical averages. If not used, the stored water gradually returns to the hydrological cycle: only about 10% remains after one year.

Given the relevance of these volumes, scaling up the method to the basin level would require careful assessment of potential upstream and downstream impacts, such as reduced lake levels upstream or altered downstream discharge due to off-season irrigation.

Climate-change scenario analyses show that, up to 2050, none of the projected years exhibit groundwater-recharge conditions comparable to those of 2022. This assessment was carried out under the RCP8.5 scenario using three regional circulation models. Nonetheless, we tested the proposed measure by reproducing 2022–23 hydrological conditions in future years and applying the average summer irrigation discharge (2.6 m^3/s) as the additional off-season irrigation flow, instead of the lower pilot value. Results indicate that this measure would have been sufficient to compensate for the missing water volume observed in 2022 and would support a faster aquifer recovery, even when accounting for additional pumping by farmers.

Best practices and recommendations

Best practices for future implementations, both in Milan and in other contexts, include developing a thorough understanding of the study area, particularly regarding water-related features such as groundwater-dependent ecosystems and soil characteristics. Monitoring is essential, selecting areas with existing long-term groundwater-level time series is advantageous, and new monitoring points should be placed close to the infiltration fields, ideally within them. The measure must also be compatible with local agricultural practices and planned jointly with irrigation consortia and farmers, ensuring that objectives and benefits are clearly shared and understood.

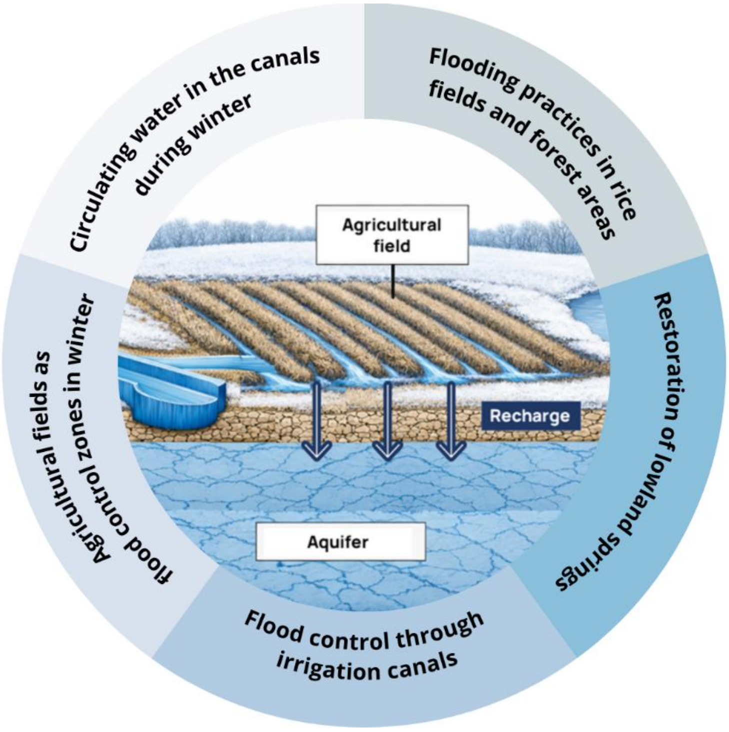


Figure 3.2.3-5: Integrated water resource management in an agricultural setting.

Being part of MAURICE enabled knowledge exchange across countries and case studies, which helped strengthen implementation strategies, research methods, and the communication of results. It also facilitated a shared understanding of how Ag-MAR can be integrated into the "Sponge City" approach promoted by the project, by harnessing the soil's capacity to infiltrate water and the aquifer's capacity to store it. Lastly, the collaboration resulted in a common framework for implementing climate change adaptation solutions, which is essential for supporting decision-making processes and guiding future large-scale applications.

3.3. Use of the infiltration capacity map from field investigation to planning, consent and decision-making

3.3.1. Introduction - the role of infiltration in stormwater drainage

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.

Infiltration is a key element of stormwater management and is essential for maintaining the natural renewability of groundwater resources. Infiltration is the percolation of water into permeable soils. The infiltration flow rate Qp (m^3/s) depends on the soil permeability coefficient k (m/s), the infiltration area Ap (m^2), and the hydraulic gradient (i), or alternatively on the depth of retained water in the infiltration facility Δh (cm). 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 relieving the public sewerage system,
- seasonal storage of groundwater (availability of natural resources),
- maintenance of the natural retention capacity of aquifers (circular economy).

Accordingly, the infiltration capacity map is an essential tool for planning climate resilient urban drainage systems. It supports informed decision making by designers, spatial planners, and permitting authorities when defining criteria for the infiltration and retention of stormwater, tailored to actual hydrogeological conditions. Spatially explicit information on soil permeability, groundwater depth, and geological constraints enables evidence based, data driven decisions in contemporary stormwater management and aquifer protection.

But besides infiltration capacity two critical questions need to be clarified in the context of the mapping.

1. 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).
2. 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.

Finally, the scale of the map should correspond with the intended use, which can be either

- 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.

3.3.2. Mapping local hydrogeological and climatic conditions; rainfall, retention and run-off

Assessment of upper layer permeability

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 geo-mechanical 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.

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

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. If granulometric analyses are available too, granulometric permeability can be estimated using established granulometric methods.

By applying statistical analysis to the estimated permeabilities and geotechnical descriptions of the samples 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. However, 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 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. In Figure 3.3.2-1 (example for Ljubljana), 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.

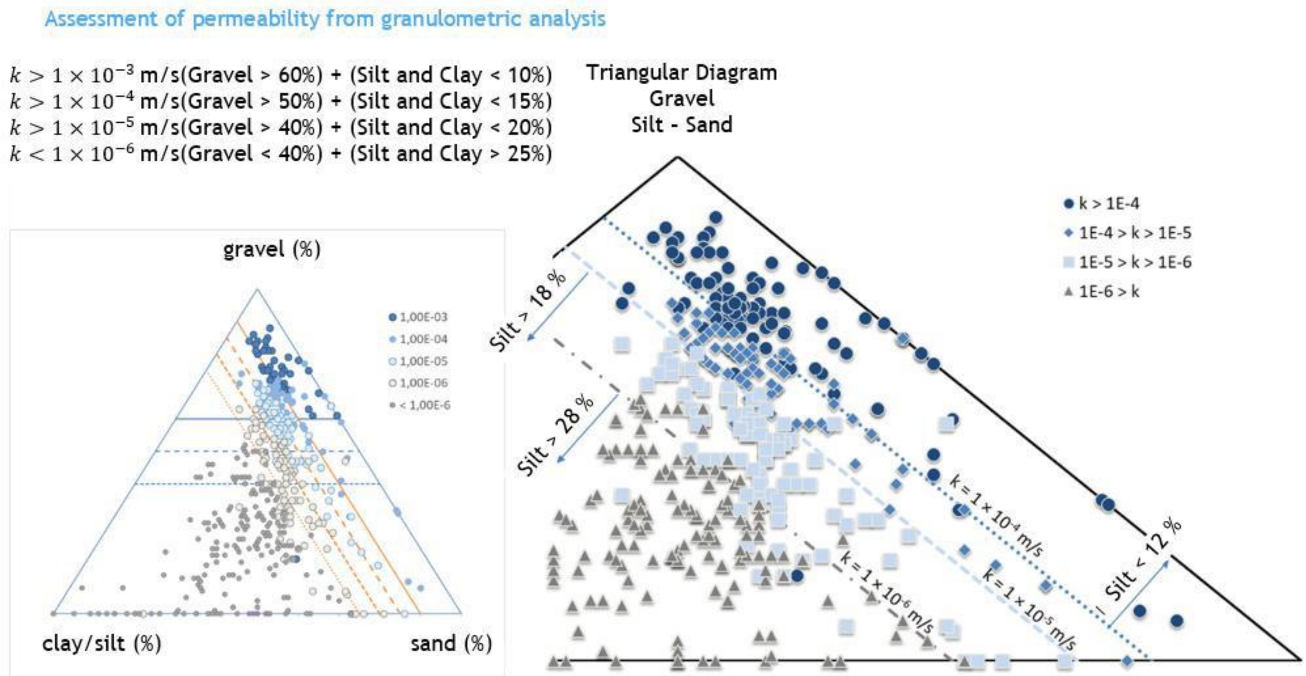


Figure 3.3.2-1: Illustration of permeability assessment for sandy gravel material based on silt content – adapted for the Ljubljana example.

Beyond such interpretations of available data and knowledge, 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 allows to 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). Tests should be performed at the intended depth of the bottom of the infiltration system and additional tests in soil layer below.

Limitations of infiltration capacity

The key question for a geotechnical engineer is how much water can effectively infiltrate?

Based on the equation 1 l/s/ha = 1×10^{-7} $m^3/s/m^2$ = 1×10^{-7} m/s it can be concluded, that for each order of magnitude in permeability factor 10 in l/s/ha applies, e.g. 10^{-6} corresponds with 10 l/s/ha, 10^{-3} with 10.000 l/s/ha. 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 as e.g. shallow or perched groundwater proximity of neighbouring buildings and soil contamination. Such limitations are dealt with in detail in D 4.4.1 – Use of the infiltration capacity map (from field investigation to planning, consenting and decision-making), Interreg CENTRAL EUROPE, 2026.

Rainfall intensity / events and their relation to infiltration

The intensity of storm events can vary significantly between cities. If the inflow of water from a storm event exceeds the infiltration capacity of the land, 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.

As an example, 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 3.3.2-2). 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.

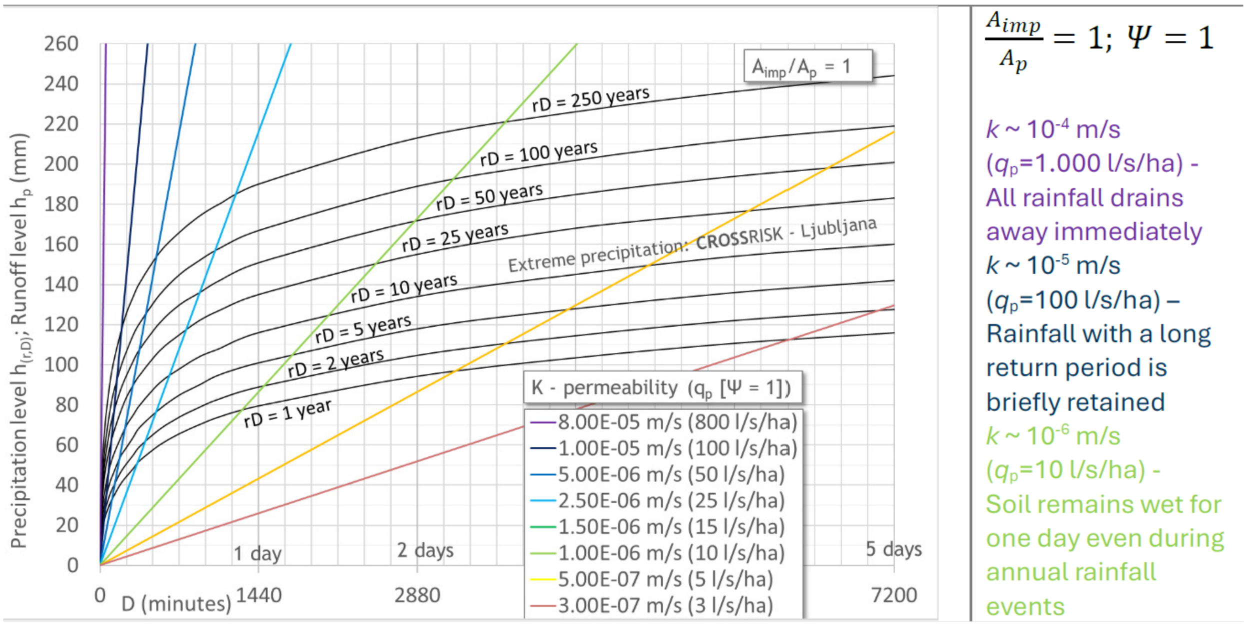


Figure 3.3.2-2: Rainfall intensity (Ljubljana example) compared to soil infiltration capacity (D = 0 to 5 days).

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 3.3.2-2 above).

A permeability of $k \geq 1.75 \times 10^{-5}$ m/s, or an infiltration capacity of 175 l/s/ha in the top layers, is already quite favourable, as during storms with a one-year return period (actual stormwater data from Ljubljana) 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. At a permeability of $k \approx 5 \times 10^{-5}$ m/s, or an infiltration capacity of 500 l/s/ha, storms with a return period of up to 10 years do not even temporarily remain in the soil. And at a permeability of $k > 8 \times 10^{-5}$ m/s, even storms with a return period of 250 years infiltrate immediately.

Runoff and retention

The natural retention capacity of rainfall on land can partially hold precipitation, preventing it from running off at full intensity. 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, Ψ_0, ranges between 0.0 and 0.3.

In most cases runoff after an intervention/construction increases significantly compared to the time before, so stormwater should 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 could infiltrate, retention or discharge into surface ditches, water bodies, or the sewer system would be unnecessary.

During a storm, when inflow exceeds infiltration capacity, retention must be provided. The specific volume V'z (m^3/m^2), or retention depth Δh (mm), depends on the ratio rA between the sealed surface Aimp (m^2) and the infiltration area Ap (m^2), the permeability coefficient k (m/s), and the storm return period r (years). This enables to develop typical curves for a given location to calculate the specific retention volume (see Figure 3.3.2-3).

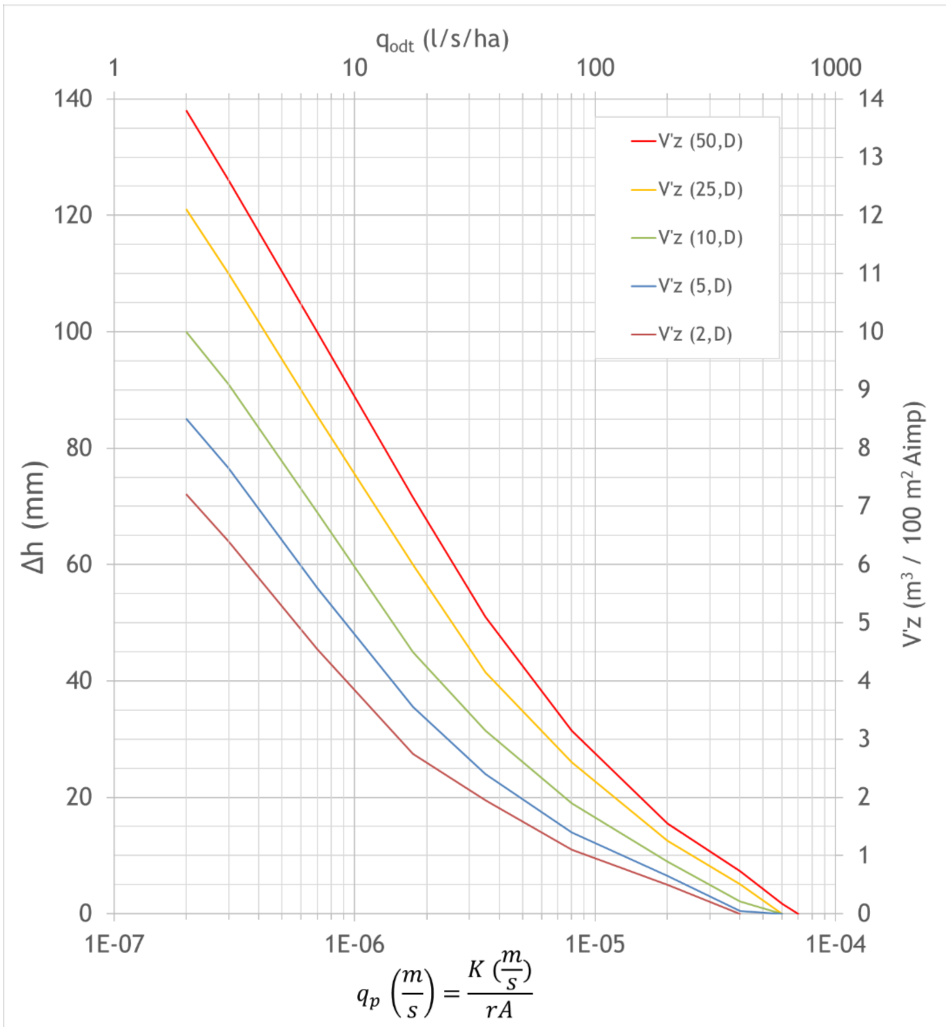


Figure 3.3.2-3: Typical curves for Ljubljana used to calculate specific stormwater retention volumes.

3.3.3. Infiltration capacity maps

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. Usually, 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.

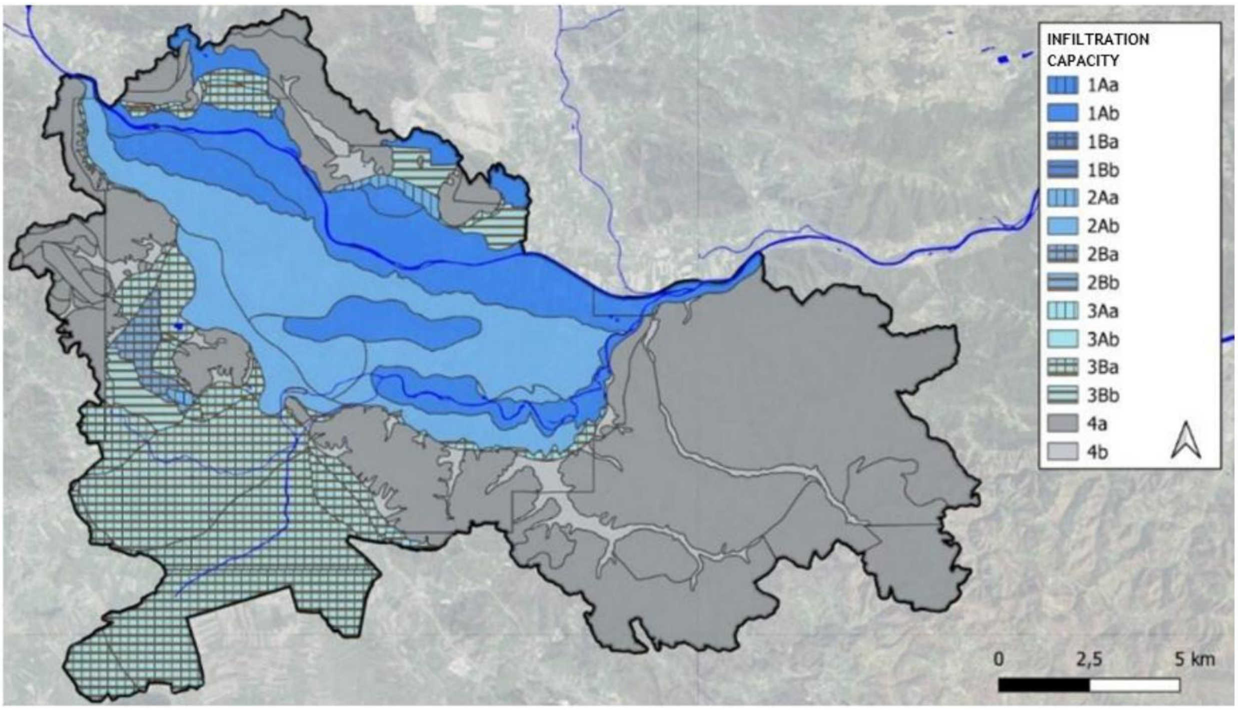
Ljubljana and Varaždin map

In the example shown for Ljubljana and Varaždin, based on local hydrogeological conditions and climatic conditions, it is appropriate to present the infiltration capacities of the top layers within its functional urban area in three classes (Figure 3.3.3-1):

1. High infiltration capacity: $qp > 1 \times 10^{-4}$ m/s
2. Moderate infiltration capacity: 1×10^{-4} m/s $> qp > 1 \times 10^{-5}$ m/s
3. Low infiltration capacity: $qp < 1 \times 10^{-5}$ m/s

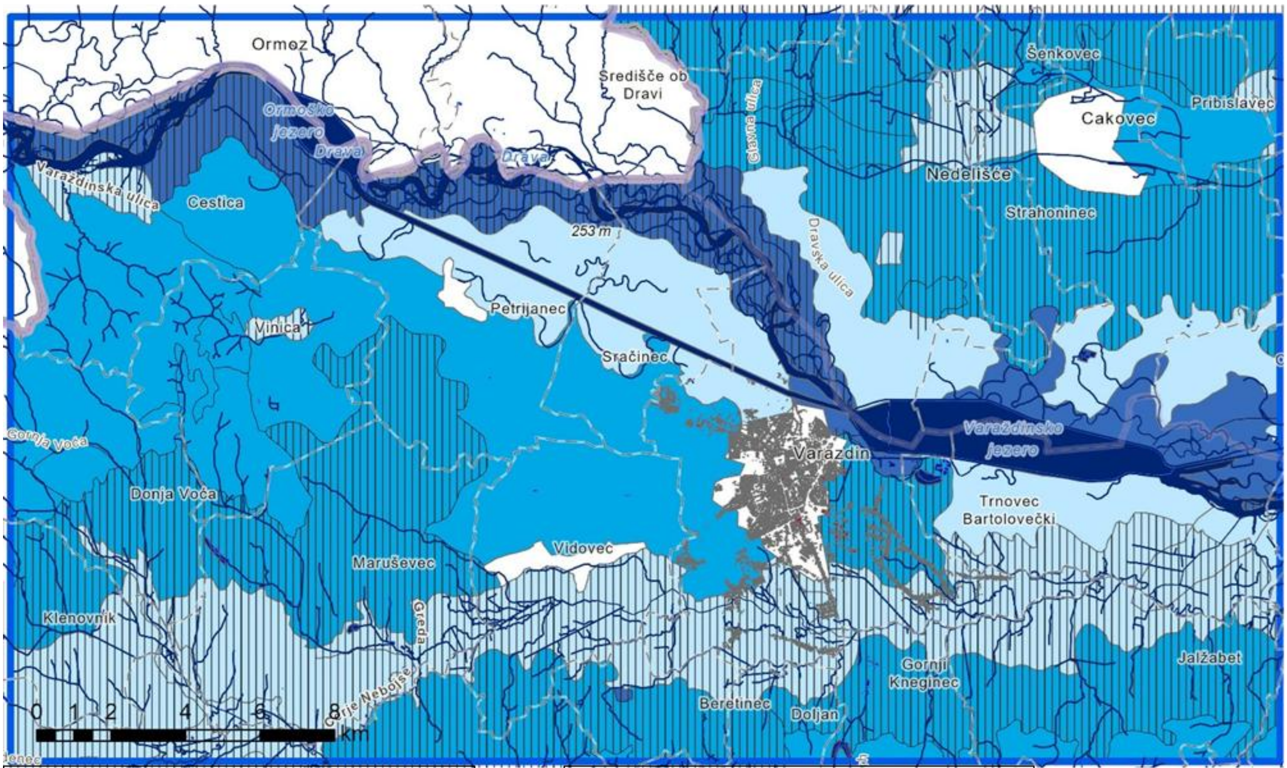
Accordingly, the infiltration capacity map presents three main categories and guidelines for infiltration:

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.



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



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

Figure 3.3.3-1: Graphical representation of the infiltration capacity map for Ljubljana and for Varaždin, showing layers based on hydraulic conductivity, confirming layer thickness and depth to groundwater.

Permitted discharge into a watercourse or, ultimately, into the sewer system should allow a value at least equivalent to the natural surface runoff of the land. This applies specifically 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.

The infiltration capacity map should include as many characteristic hydrogeological cross-sections as possible, illustrating all typical top layers according to their infiltration capacity. Such cross-sections should indicate the permeability category, groundwater level, perched groundwater tables, and the thickness of cover layers.

Making use of the map

Such maps provide a scientifically sound spatial differentiated knowledge base for the development of climate resilient urban drainage policies. The use of the infiltration capacity map enables:

1. Reduction of flood risk – critical peak roof runoff is more efficiently managed through distributed infiltration.
2. Enhancement of natural aquifer recharge – compensating for anticipated reductions caused by climate change.
3. Improvement of degradation and dilution potential – essential in areas with exceedances of nitrate, e. g. Cr(VI), benzotriazole, and pesticides.
4. Integration of drainage and spatial planning – hydrogeologically justified criteria replace general normative values.
5. Justification of restrictions and requirements in permits – for example, allowable discharge, minimum distances of infiltration fields, and selection of appropriate systems.

The infiltration capacity map therefore serves as a core technical foundation for implementing sponge city concepts and for integrated groundwater protection and stormwater management under climate altered conditions. It transforms heterogeneous geological and hydrological data into spatially specific design and permitting criteria, enabling: (i) mitigation of peak runoff through distributed infiltration; (ii) maintenance of aquifer recharge; (iii) reduction of the need for sewer infrastructure investments by means of local retention; and (iv) risk reduction (quality, stability, impact zones) through clear exclusions and constraints.

3.4. Surveying urban water mass flows and contaminants to set resilient drainage and infiltration targets

3.4.1. Introduction

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

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

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

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

These changes affect groundwater level changes, groundwater flow directions, and water flow through the aquifer as well as the operation of sewer networks, which will find it even harder to cope with increased loads. Therefore, possible solutions are being discussed, such as the introduction of rainwater infiltration systems, retention of water in urban environments, and the promotion of the natural hydrological cycle. These measures require coordinated action by various stakeholders, including city authorities, water management experts, urban planners, and local communities.

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

3.4.2. Mass balance for water cycle and contaminants

Systematic monitoring of water mass flows and contaminants in urban areas is essential for shaping climate resilient stormwater management objectives, protecting groundwater, and planning effective drainage systems. The developed concept integrates hydraulic, hydrogeological, and mass balance methods to assess where, and to what extent, stormwater surpluses occur within the functional urban area, as well as where contaminant inputs, transport, or accumulation take place.

A holistic approach to monitoring water mass flows

The concept is based on a simplified water balance at the scale of the functional urban area, using the same key parameters as those applied in the development of infiltration capacity maps:

- Effective precipitation (Pef) as a major source of aquifer recharge.
- Recharge from precipitation (Qrec), primarily determined by the degree of urbanisation and the proportion of impervious surfaces.
- Recharge from surface water bodies (Qriver) and changes in stream–aquifer interactions.
- Changes in groundwater levels (dGWL), which influence infiltration feasibility and associated risks.

- Changes in flow direction (dω), which determine contaminant pathways in the aquifer.
- Through aquifer flow (Qgw), which controls the aquifer's dilution capacity for contaminants.

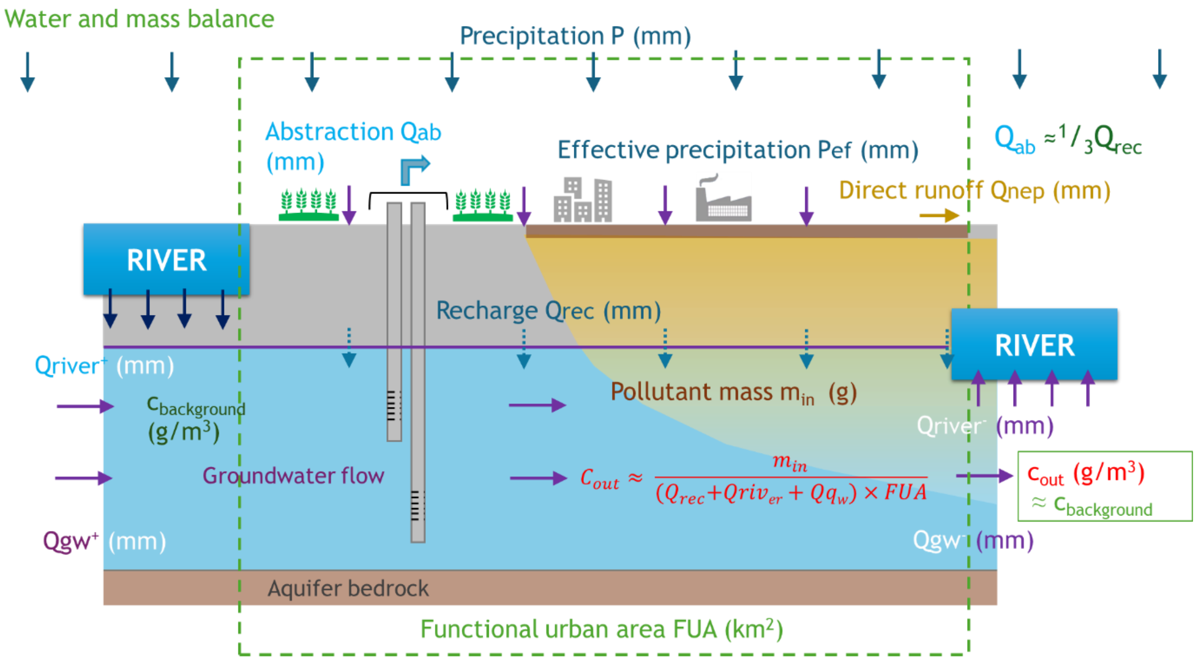


Figure 3.4.2-1: Schematic representation of key elements of the water and mass balance.

A change in groundwater level (ΔH) in the aquifer means a change in groundwater reserves and retention capacity, but also affects underground constructions, the geotechnical stability of foundations and slopes, and the natural retention capacities for contaminants. Changes in flow through the aquifer resulting from changes in recharge from the river or precipitation means a change in pollutant dilution, i.e., an increase or decrease in their concentrations. The change in flow results from a change in recharge from the river or precipitation. Changes in groundwater flow direction, including deviations in flow direction, also lead to deviations in the path of pollutants and may consequently affect the use of groundwater.

Mass balance of pollutants and methods for monitoring contaminants

With increasing settlement, agriculture, and industry, the pressures on groundwater quality have greatly increased. High concentrations of nitrates and pesticides have appeared regionally, and more localised pollution due to emissions and losses of substances from industry, such as chromium (CrVI) and organic solvents (PCE, TCE). Today, we are additionally faced with ever new numerous pollutants that come with the increasing production of synthetic substances and products. These are mainly residues of pharmaceuticals, plasticisers, corrosion inhibitors, microplastics, and others.

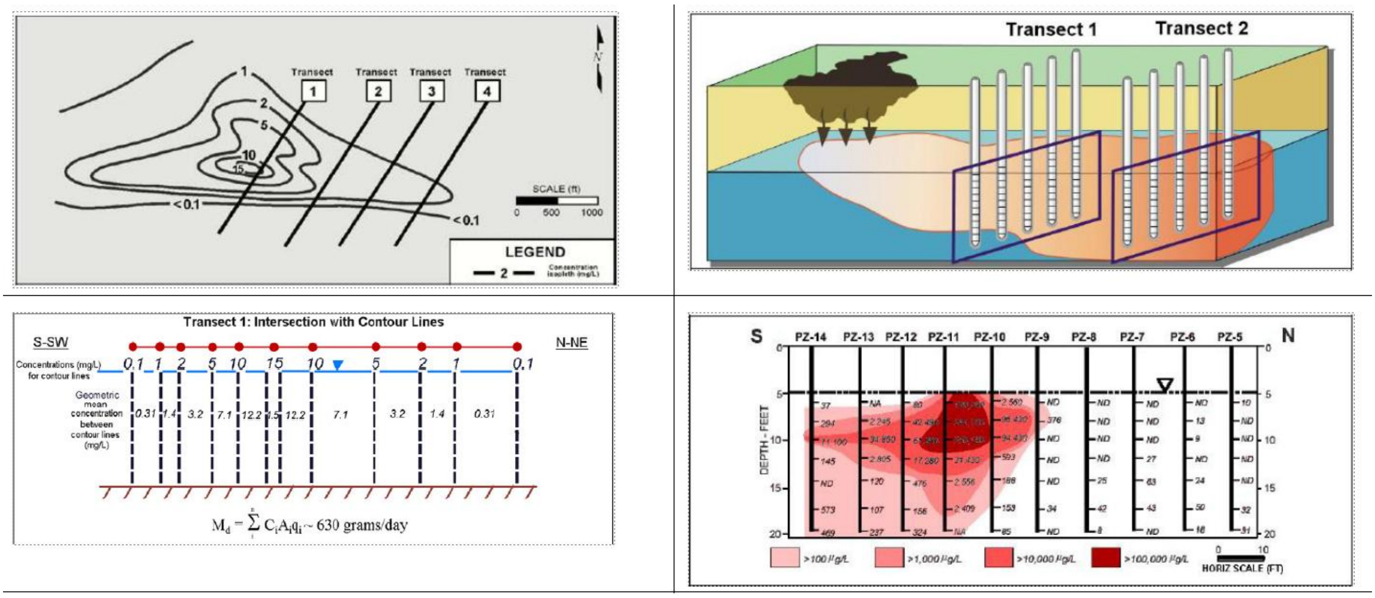
For monitoring surpluses in groundwater, pollutants can be divided into two characteristic groups:

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

To assess contaminant fluxes, the concept employs two complementary methods that together capture both, point and diffuse sources:

Transect method for point sources

For pollutants that spread in a characteristic pollution plume, the transect method is most commonly used (Newell et al., 2003; Farhat et al., 2006). Depending on the availability of spatial data, it can be used in 2D or 3D analysis of the area. The method is based on setting a control plane perpendicular to the main direction of groundwater flow, which is divided into representative sections according to measured pollutant concentrations. For each section, the partial mass flow is calculated, taking into account the Darcy velocity and the area of each section, see Figure 3.4.2-2.



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

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

Figure 3.4.2-2: Examples of the use of the transect method in 2D and 3D areas (Source: Newell et al., 2003, Farhat et al., 2006).

This method enables the determination of:

- partial mass fluxes through individual segments of the transect,
- local concentrations at defined monitoring points,
- Darcy velocity and the effective flow cross section.

The following figure illustrates the application of this method in Ljubljana, where it was widely used during the project.

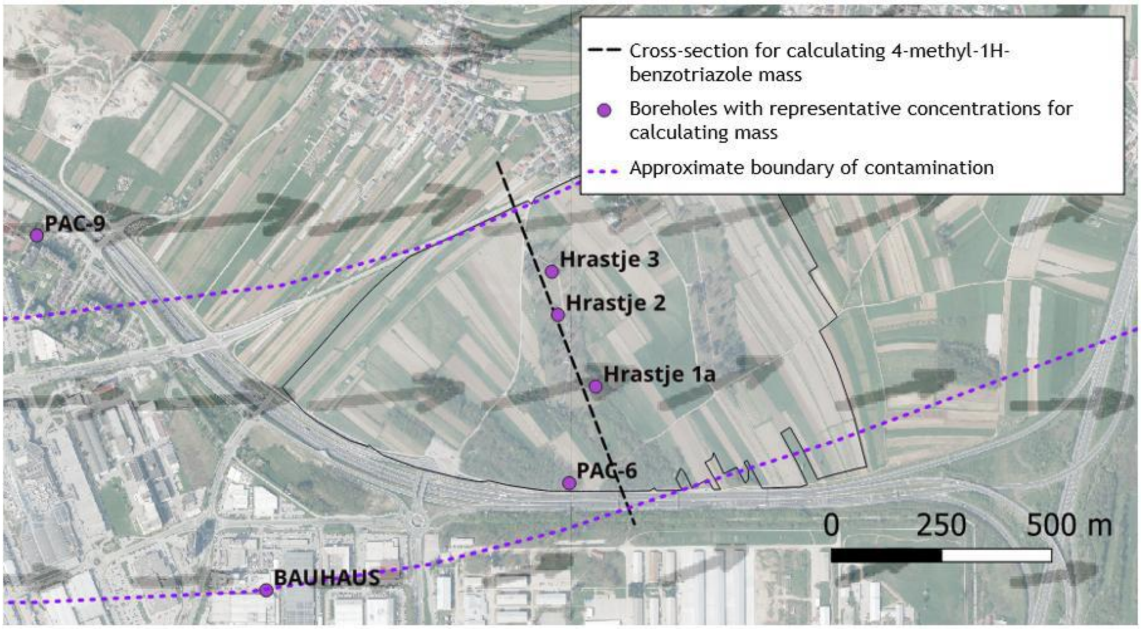


Figure 3.4.2-3: Example of a contamination plume with benzotriazole and the selected transect with defined measurement points.

Mean concentration method for diffuse sources

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

- extensive monitoring networks (type A and type B monitoring points),
- concentration time series,
- hydrogeologically determined mass fluxes.

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

- Type A: measurement points that are part of regular monitoring, with at least twice-yearly seasonal analysis and are well distributed spatially, so that they can represent the characteristics of the distribution and transport of pollutants in the water source;
- Type B: measurement points that have the longest continuous time series of observations and can continue to be maintained for the purpose of tracking long-term trends.

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

3.4.3. Linking mass balance, contaminants and drainage objectives

Applying a climate resilient drainage concept with a focus on infiltration and retention requires an integrated perspective. It is the key contribution of the concept developed by the project to integrate these three dimensions: water quantity, water quality, and hydrogeological constraints. This integration enables the definition of targeted drainage objectives (how much water may be discharged, infiltrated, or retained), infiltration objectives (where infiltration is acceptable, recommended, or prohibited), and water quality objectives (permissible mass fluxes based on dilution potential).

In this context, roof water and its preferred redirection to infiltration builds the most prominent and influencing block. The report D.4.4.2 includes detailed recommendations how to deal with this issue. For the design of Retention-Infiltration Systems, the key boundary conditions that limit and guide the planning include:

- Design rainfall event: 3 the initial stormwater load is selected, e.g. rainfall of a certain intensity and duration with a given return period (n years) for the area in question.
- Permissible discharge to the public network (Q_{per}): If part of the stormwater is allowed to be discharged into the sewer, the designer must take this limitation into account. It is usually determined by technical guidelines or the consent of the operator; it represents the capacity of controlled discharge that is still acceptable for the existing network.
- Soil permeability and infiltration capacity (k): These are determined based on geological investigations and indicate the rate at which the substrate absorbs water (m/s). Together with the available infiltration area (e.g. infiltration field or shaft area), k determines the system's maximum infiltration flow (Qinf).
- Local constraints and safety factors: Boundary conditions must also take into account possible high groundwater levels, protected water protection areas, restrictions due to the proximity of buildings and infrastructure. These conditions may limit the depth of infiltration or require additional measures.

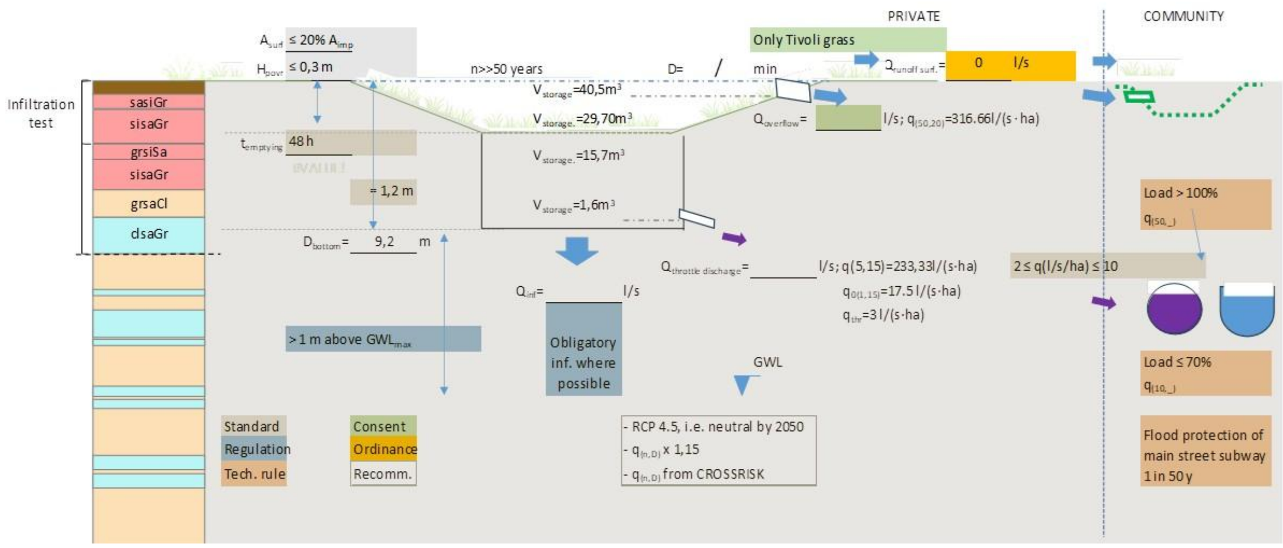


Figure 3.4.3-1: Illustration of types of boundary conditions for the design of retention-infiltration fields.

The listed boundary conditions define the framework within which the calculation and design of the retention-infiltration system take place. When designing a specific system, these parameters must be balanced: if the permissible discharge is small, the system must allow for greater infiltration or retention; if soil permeability is low, a larger retention volume must be provided, etc. A comprehensive consideration of boundary conditions ensures that the final system will safely handle the intended rainfall event and contribute to reducing flood risk and improving water status in the urban environment.

3.4.4. Definition of climate resilience objectives

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

As an example, Varaždin has defined a concept for planning and decision-making in urban drainage management. The city council of Varaždin has adopted a Decision on Guidelines for Sustainable Stormwater Management, which includes a new framework and directions for future drainage arrangements. In addition, an early warning system has been established in Varaždin to monitor pollutant surpluses in groundwater, and new financial and technical mechanisms have been introduced to encourage the reuse of collected rainwater (e.g. for irrigation) and relieve the sewer system. These measures increase awareness and readiness for rapid action in the event of deviations (e.g. if monitoring detects a rise in hazardous substance concentrations).

As a general conclusion, monitoring water mass flows and contaminants enables:

1. the establishment of realistic infiltration targets aligned with contaminant impact zones,
2. reduction of the risk of contaminant migration into protected areas,
3. prediction of drainage system responses to extreme weather events,
4. determination of permissible mass fluxes and optimisation of retention systems,
5. integration of drainage management with groundwater protection at both quantitative and qualitative levels.

This concept therefore serves as a tool that complements the infiltration capacity map and enables drainage and infiltration targets to be climate resilient, scientifically grounded, and consistent with the carrying capacity of the urban aquifer.

3.5. Guideline for public administration to implement the beneficial rainwater management (RM)

3.5.1. Introduction

This section is built on the MAURICE “**Guideline for Public Administration to Implement Beneficial Rainwater Management**”; which presents a methodological guide for cities and municipalities for various levels introduction of RWM.

The increasing impacts of climate change include torrential rains and local floods becoming more frequent. At the same time, urban environments are overheating, groundwater levels are falling, and the quality of public spaces is deteriorating. The traditional method of dealing with rainwater, which for decades was based primarily on its rapid removal sewerage outside built-up territory, it turns out like long-term unsustainable.

Modern approach to rainwater management (RWM) is based on a different principle. Rainwater already is not understood like a problem that needs to be solved as quickly as possible, but as a valuable natural resource. The goal is to retain water, to allow its absorption, use her directly at the point of impact and support its natural cycle in the environment city (Sponge City concept).

This approach today represents one of the key components of urban adaptation to climate change and at the same time an important tool for sustainable urban planning.

Historical urban development for a long time was based on rapid drainage of water from streets, roofs and public spaces. Such an approach has brought significant hygienic and technical advantages, but gradually started to manifest its negative consequences.

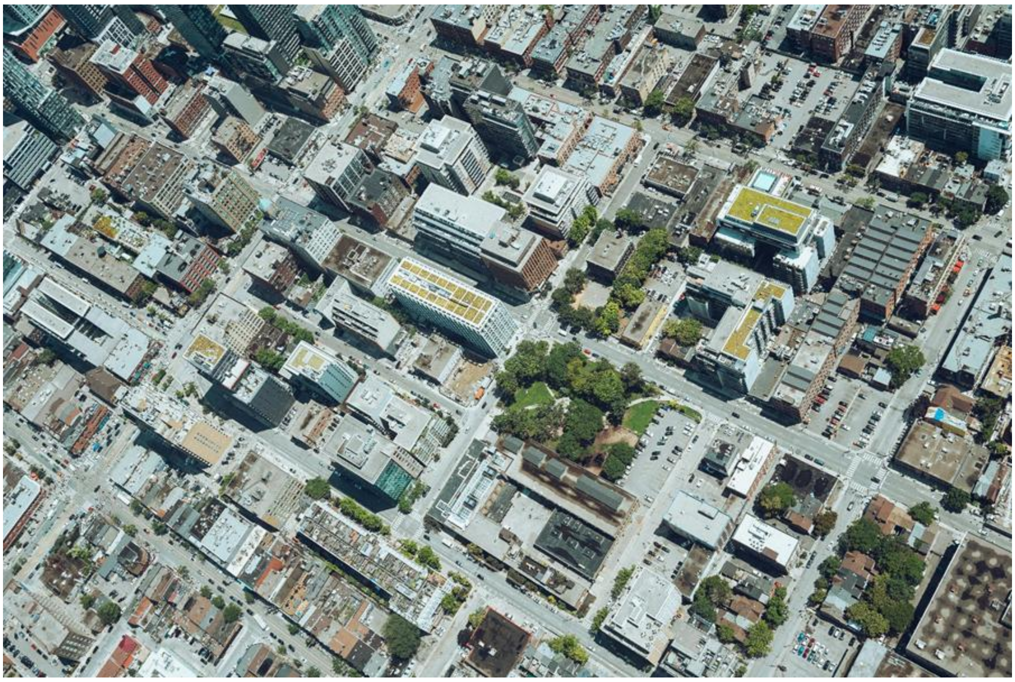


Figure 3.5.1-1: Urbanized areas are characterized by a high proportion of impervious surfaces.

Large areas of asphalt and concrete significantly limit the infiltration of water into the soil. Rainwater quickly drains after surface, overloads sewage and increases risk local flooding. At the same time, groundwater is not being recharged sufficiently and cities are losing their ability to cool naturally.

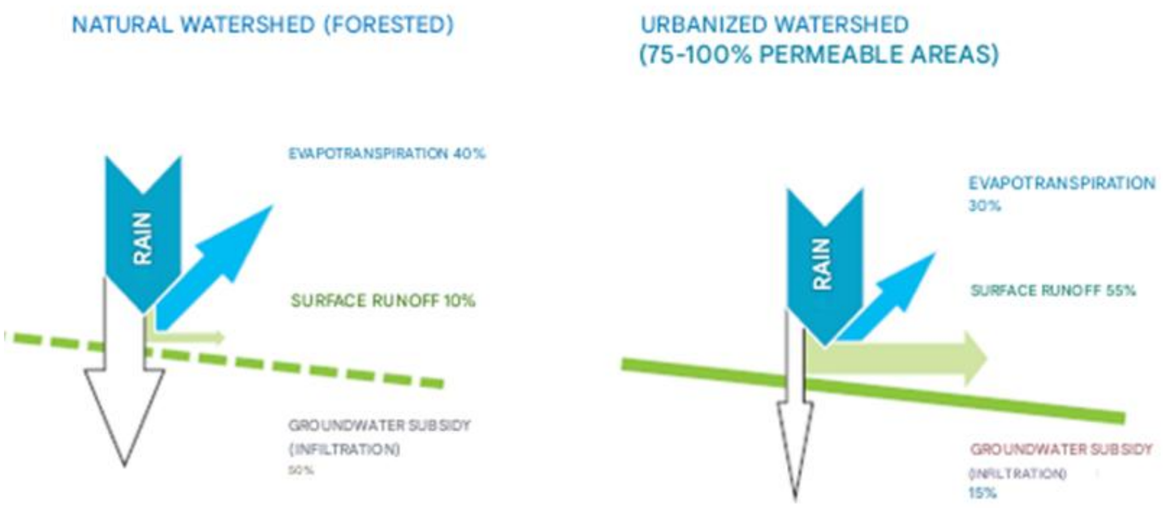


Figure 3.5.1-2: Comparison of rainwater runoff in a natural and urbanized catchment.

Overheating of urban environments is one of the most serious problems of modern cities. Asphalt, concrete and more reinforced surfaces accumulate heat and during summer months create a significant urban heat island effect. Lack of vegetation and water in the environment limits naturally cooling through evaporation.

Therefore, rainwater management cannot be understood only like insurance fast drain rain water into the sewerage system. This is a complex issue related to the quality of life, protection life environment, public health and economic stability cities. This guidance and best practise provided by the MAURICE project intends to support urban local governments and urban public administration in introducing modern and sustainable rainwater management.

3.5.2. Main principles and obstacles for sustainable rainwater management

One of the most important principles sustainable RWM is an effort to imitate natural aqueous regime landscape. In the natural environment most water gradually soaks into the soil, part evaporates through vegetation and only small amount drains after surface area, see Fig. 2. In urbanized environments however this natural cycle significantly disrupts.

RWM is founded on principle: " Water should to stay as close as possible to the place where "falls". Applying this principle in urban areas would respect natural hydrology and ecology and contribute to the restoration natural cycle water. This leads to three **basic rules in RWM**:

1. Reduction and transformation of stormwater runoff takes place on the land, i.e. at the place of stormwater impact and at the owner's ownership (the device that reduces runoff is an integral part of the structure being drained);
2. Stormwater is not mixed with wastewater - this is the only way it can be effectively evaporated, percolated or used for home operation;
3. The amount of stormwater runoff from a built-up plot is the same as the amount that would run off from the natural land surface

Main obstacles often lie in the area of legislation, finance, urban administration, but also in public awareness. Identifying these obstacles and designing ways to overcome them is an essential part of a city's strategy for RWM implementation.

These obstacles to the implementation of rainwater management need to be addressed at all levels – with the support of the European Union and its institutions, at the national as well as at regional and local levels. Next table summarizes recommendations for each level.

<table>
<tr><th colspan="3">Level</th></tr>
<tr><th>European/national</th><th>regional</th><th>local</th></tr>
<tr><td colspan="3">political and strategic areas</td></tr>
<tr><td>creation of understandable and unambiguous rules of legislative rules</td><td rowspan="3">unification of the regional administration's approach to the interpretation of existing legislative regulations</td><td>unification of local government's approach to the interpretation of existing legislative regulations</td></tr>
<tr><td rowspan="2">development of European and national standards for RWM</td><td>active approach to promoting the water management concept</td></tr>
<tr><td>enforcement of RWM rules during construction and renovations</td></tr>
<tr><td colspan="3">economic and financial areas</td></tr>
<tr><td>financial incentives and subsidy programs</td><td rowspan="2">financial incentives and subsidy programs</td><td rowspan="2">financial incentives</td></tr>
<tr><td>cancellation of exemptions for payment for discharging rainwater into the sewer system</td></tr>
<tr><td colspan="3">institutional and organizational area</td></tr>
<tr><td rowspan="3">training and education of officials and politicians</td><td rowspan="3">training and education of officials and politicians</td><td>training and education of officials and politicians</td></tr>
<tr><td>establishment of interdepartmental working groups for the coordination of RWM projects</td></tr>
<tr><td>establishment of the position of administrator of the city's water management concept</td></tr>
<tr><td colspan="3">social and cultural area</td></tr>
<tr><td rowspan="2">awareness campaigns and education</td><td rowspan="2">awareness campaigns and education</td><td>awareness campaigns and education</td></tr>
<tr><td>citizen involvement in RWM projects</td></tr>
<tr><td>examples of good practice</td><td>examples of good practice</td><td>examples of good practice - exemplary implementations of RWM in public buildings</td></tr>
</table>

Level		
European/national	**regional**	**local**
technical and operational area		
support local and regional authorities by providing sufficient and reliable data (free of charge data from government institutions)		sufficient and reliable data for dimensioning RWM measures (analysis of climatic conditions and their variability)
		Incorporating RWM principles into spatial planning, development documents and decision-making processes of urban administration
		processing of analyses of rainwater runoff in individual parts of the city (hydrological analysis, hydraulic capacity of the sewerage system, analysis of the infiltration potential of the area, analysis of the possibilities of using rainwater in the city)
		assessment of risks associated with managing rainfall in the city
		setting general drainage limits
		introduction of standards for the application of RWM for new and renovated buildings
		consistent control and enforcement of RWM by public administration

The EU and a number of Member States are aware of the importance of RWM for the sustainability of water management and the quality of life in urban environments, therefore they allocate various subsidy titles for its successful implementation. MAURICE report D.3.4.1 provides an overview of relevant of the subsidy sources in the EU and the partner countries of the MAURICE project. Innovation, pilot and demonstration projects can be funded at EU-level by e.g. "Climate Change Adaptation" (Horizon Europe, Mission 3), LIFE and INTERREG, and at national level similar programmes are available in most of the countries involved. The European Regional Development Fund (ERDF) & Cohesion Fund (CF) feeding national and regional operational programmes is the most important and relevant leveraging programme for practical implementation in the cities, complemented by specific national subsidies available.

3.5.3. Procedures for introduction of rainwater management in cities

Concept for implementation of rainwater management for the entire city area

Rainwater management (RWM) cannot be seen as a set of individual technical measures, but as a long-term strategy for the entire city. Success is conditional on a conceptual approach – i.e. the integration of RWM principles into spatial planning, development documents and decision-making processes of the city administration. A strategic approach to rainwater management (RWM) at the city level requires that individual steps be interconnected, systematically managed and supported by current knowledge from hydrology, urban planning and landscape engineering. Professional literature clearly points out that random and isolated measures often do not fulfil their purpose and can lead to inefficient use of investments.

The steps below represent a methodological framework for developing a RWM concept in an urban environment. In particular, it is necessary to focus on:

- Assessment of rain water runoff and Infiltration potential in individual parts cities
- Assessment climatic conditions and their variability
- Assessment risks associated with rainwater management in city

- Determination general limits drainage for the city like whole
- Introduction RWM standards for new and renovated buildings
- Integrating RWM into strategic documents (city plan, climate strategy cities, action plan for adaptation on change climate etc.)

Implementation of rainwater management in undeveloped areas parts cities

Unbuilt areas represent unique opportunity for inclusion principles rainwater management (RWM) to the city frames still before by starting construction. It is therefore necessary to apply systematic and integrated approach that connects territorial planning, legislative framework and measures close nature. In particular, it is necessary to:

- processing hydrological, soil and urban studies for the given territory,
- to approach the undeveloped territory as a whole,
- consistently apply principles sustainable RWM.

Implementation of rainwater management in built-up areas of cities

Such areas taken together make up the largest part of a city. Unfortunately, implementation of rainwater management water (RWM) in built-up areas is from a number of reasons such as are spatial limitation, high share impermeable surfaces and complex structure proprietary relationships, etc., significantly more complicated than in undeveloped areas. Nevertheless, even under these conditions considerable benefits for urban environment and quality of life for residents can be achieved when applying suitable technical and organizational measures.

A suitable means for implementing RWM is to analyze the potential of existing development so that the precipitation runoff from the area approaches natural conditions. On its basis, it may be possible, for example, to disconnect certain parts of paved areas in a defined area of existing development from the sewer system.

Implementation rainwater management for specific buildings (projects)

Rainwater management (RWM) on the level of individual buildings represents the most specific level of RWM implementation. While strategic documents and territorial planning determine general framework, only, construction permits and project documentation decides whether and how RWM principles will be really implemented. The document “Guideline for Public Administration to Implement Beneficial Rainwater Management” mainly emphasizes the role of public administration at control and enforcement for application of RWM in individual buildings and construction projects.

The document also provides a practical example of “Proper procedure for builders when applying rainwater management principles (RWM)”.

3.6. Guideline for the selection of rainwater treatment technologies for further use

3.6.1. Introduction

This section is built on the MAURICE "Guideline for the selection of rainwater treatment technologies for further use", which presents recommendations technologies fit für purpose and related economic considerations.

Rainwater harvesting represents a viable and sustainable alternative for water supply, especially in the context of increasing water scarcity and the need to relieve pressure on central infrastructure.

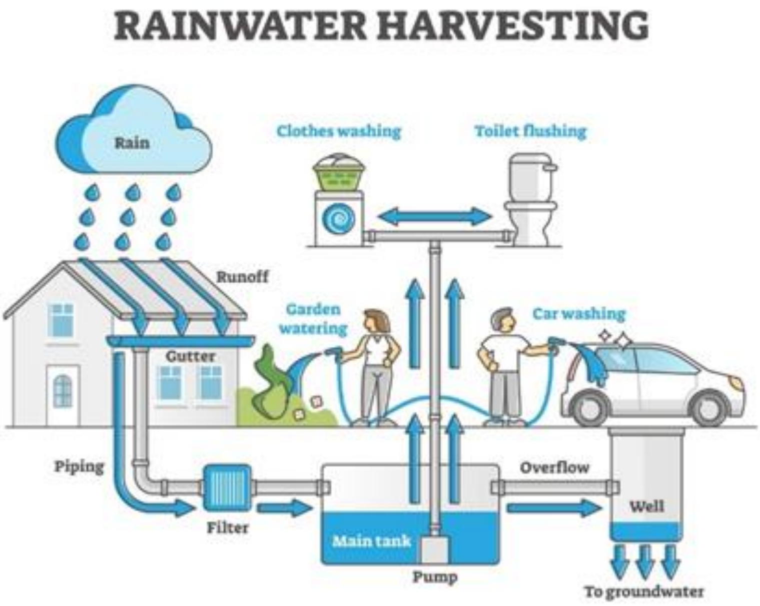


Figure 3.6.1-1: Rainwater harvesting diagram – conventional (allamericangutterprotection.)

Rainwater systems not only reduce freshwater consumption but also offer co-benefits such as flood mitigation, improved urban microclimates, and energy savings. However, to fully leverage these advantages, a holistic approach is needed—considering catchment design, storage, appropriate treatment technology, economic feasibility, and maintenance.

Rainwater treatment is a future way of sustainable use of water, which depends on factors such as the average rainfall in the region, water contamination, environment, surrounding location, air contamination, and many others. The main problem regarding rainwater is that even though the majority of the water went through evaporation to a gas state which left some of the contaminants like salts, metals, or bacteria in solid residue, there are still volatile contaminants such as NH3 or SO2 which can change the water Ph level (acid rains) thus making the water toxic.

The biggest problem starts when the water from the rainfall falls. Water is contaminated by running over the roofs or streets by various types of contaminants such as pathogens from animal excrement, heavy elements from the materials on roofs, organic compounds from residues, and others.

This all leads to lower water quality and increased health risks for the general population as well as for it is surroundings including agriculture. Rainfall treatment is an effective method how to reduce the stress on wastewater treatment facilities and save water & money. For achieving economic solutions, it depends on several factors to choose the best cost-effective technology-based of factors such as the environment and location coupled with its desired use. Due to relatively high inputs, the return of investment depends in many cases on grants and financial support "green solution → financial aid".

3.6.2. Rainwater quality

One possible source of water is rainwater. Its quality plays a key role in its usability. Generally, the rainwater is soft, slightly acidic which has advantage for some type of the use. Therefore, it is necessary to characterize rainwater, identifying sources of contamination. This will make it possible to prevent contamination or to develop technology for its treatment and thus increase its usability. Another aspect is to determine the quality of rainwater due to environmental contamination. As will be shown later, rainwater is relatively clean, and the main contamination occurs when it reaches the surface. The surface itself and the location of the abstraction then play a major role in the resulting quality of the rainwater.

The tailored solutions and approach to cleaning of rainwater can be physical, chemical, or even hydrological which all have different inputs and can purify the water differently. Sometimes, a combination of two or more techniques gives the best cost-effective solution for the desired water quality level, depending on a thorough classification of the contamination.

The following rainwater contaminants need to be considered:

Atmospheric contaminants

- Oxides of sulphur (SO_2, SO_3)
- Carbon dioxide (CO_2)
- Dust, pollen, volatile organic contamination

Contaminants from contact to materials until collection

- Asphalt on roads, release of polyaromatic carbons
- Iron roofs ▫ Cu, Pb, Zn, Cd
- Green roofs = roof garden can influence the colour and turbidity of the Water

Organic compounds and other pollutants

- Leftovers of pesticides and herbicides from atmosphere, facades or fields
- Oil contamination, e.g. from parking lots etc.
- Excrements of birds and mammals → organic contamination that supports the growth of microorganisms and the creation of pathogens causing potentially diseases

Analyses of rainwater from roofs in Novy Bydzov showed that out of 180 parameters analysed as main pollutants only microbial contamination proved to be relevant. Such contamination is caused by bird droppings, leaves and insects and goes far beyond E. coli. Similar results were obtained from other partner cities Jaworzno, Varaždin, and Ljubljana. Condition and type of roofing materials could play a significant role on runoff quality too. Roofs made out of metal give off increased concentrations of Zn, Pb and Cu into runoff. Of course, the older the surface on the roof, the more pollutants it releases.

Rainwater collected at the ground in urban areas, such as roads and parking lots, often carry many pollutants. Main pollutants found in this water are Total Suspended Solids (TSS) which comes from dust, sand and road ashes. Heavy metals are also common pollutants (Zn, Cu, Pb, Cd). They come from vehicle emissions and tires. Hydrocarbons and oil residues from fuel leaks and asphalt degradation also often pollute rainwater. Another main contaminant are microplastics, tire wear particles and anti-cooling mixtures.

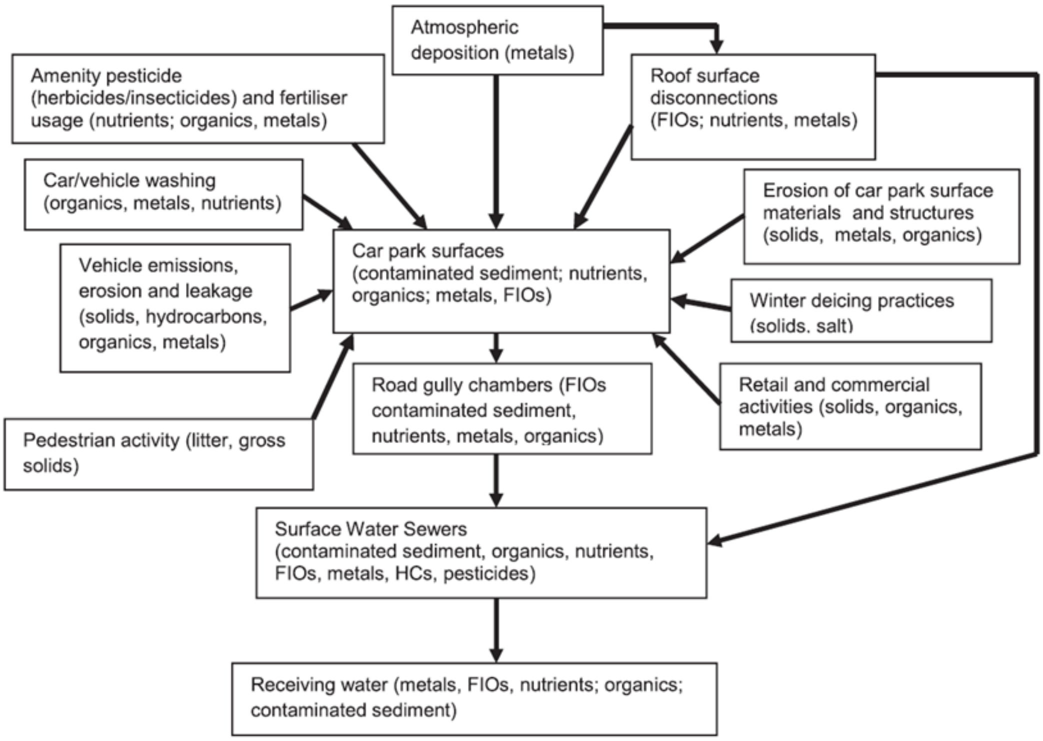


Figure 3.6.2-1: Principal sources and pathways of pollutants contributing to car park runoff (Lundy 2014)

Rainwater is one of the possible sources of water, but to make it usable it is necessary to choose technologies that ensure the required quality. In all cases, the first flush effect has a great influence on the 6uality. The water quality in the first minutes of rain is much lower than the water quality later.

3.6.3. Harvesting of rainwater

Designing an efficient rainwater harvesting system starts with separating water streams based on their intended use, followed by smart pre-treatment like screens and first flush diverters. To ensure water safety and usability, systems often include sedimentation units and underground storage tanks made of durable materials. For added sustainability, combining storage with infiltration supports groundwater recharge. Real-time monitoring and modelling help fine-tune the system, especially in regions like Czechia, where storage for at least 21 days is advised based on local rainfall data.

Domestic rainwater harvesting is locally feasible, widespread implementation in urban areas can contribute to multiple water management objectives which has important direct benefits:

- Provides non-potable water source
- Reduces demand from distribution system - Could supply up to 50% of the domestic demand
- Mitigates urban floods
- reduces water pollution by reducing the combination of combined sewer overflows (New Directive to urban wastewater management)
- Preserves high-quality water sources

Non direct benefits include the reduction in the need to upgrade water infrastructure (distribution and sewer system) as well as energy saving and emission reduction due to reduce water abstraction, transport and treatment.

In households, rainwater is mainly used for toilet flushing (60%), Washing machines 20%, Irrigation (15-20%), surface washing and boilers.

Domestic rainwater harvesting systems should include:

- Roof, gutter protection screening, gutter, rain head, first flush diverter, tank screen, tank, insect proof flap valve, auto-fill system, pump system, irrigation filter, water level sensor (indicator)
- Roof painting without heavy metals
- First flush diverter for the first 3-5 mm of rainfall
- Storage tank operated by gravity or pump (outside or underground), which should contain at least 40% of runoff volume – in Czechia average storage volume should cover 21 days of consumption.

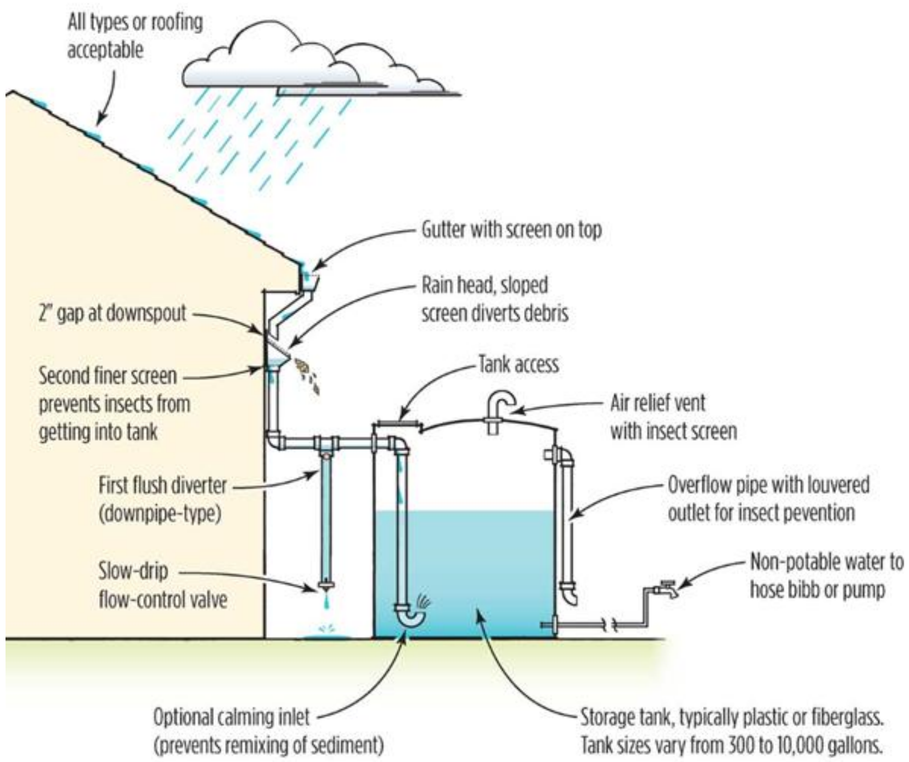


Figure 3.6.3-1: Rainwater harvesting system diagram (energy.gov).

With its guide "The 12 Steps of Rain Harvesting™" https://rainharvesting.com.au/ Australian colleagues provide a good illustration how to establish domestic rainwater harvesting systems. Also from the US https://www.energy.gov/cmei/femp/rainwater-harvesting-systems-technology-review a wealth of structured information is available.

3.6.4. Treatment of rainwater

We distinguish between the two main sources of rainwater, those from roofs and ground surfaces as roads, parking lots or other kind of free space. The catchment system is crucial because it determines the quantity and quality of collected rainwater. A well-designed catchment (e.g. roof, ground surface) ensures efficient collection, minimizes contamination, and protects downstream treatment components. Its material, slope, and cleanliness directly affect system performance and water safety.

Treatment of rainwater from ground surfaces often relies on infiltration systems, which allow water to percolate through soil layers, naturally filtering out sediments, nutrients, and pollutants. Common systems include infiltration trenches, swales, and permeable pavements.

Concerning treatment of rainwater from roofs the purpose of use defines the treatment technology. Use for agriculture and garden-management as well as flushing toilets requires minimal treatment. If it should be used for showering or even for full-scale integration into the home's water system, which includes potable uses too, the quality of the filtered and cured water and respectively the treatment standards applied are much higher.

Depending on the amounts of water / daily flows and the use case different treatment technologies can be applied. Figure 3.6.4-1 provides an overview and classification for such technologies.

Category	Technology	Sustainability	Costs	Category	Technology	Sustainability	Costs	Category	Technology	Sustainability	Costs
Passive Treatment	Slow Sand Filters (SSF)	Highly sustainable, low maintenance	Low setup, minimal maintenance	**Conventional Technologies**	Rapid Sand Filters	Moderate sustainability, requires energy	Medium setup, periodic maintenance	**High-Tech Technologies**	Ultrafiltration (UF)	Energy-intensive, effective for multiple contaminants	High cost, membrane replacement needed
Passive Treatment	Constructed Wetlands (Vertical Flow)	Highly sustainable, natural-based	Medium setup, low maintenance	**Conventional Technologies**	Coagulation-Flocculation	Chemical use, generates sludge	Medium setup, recurring chemical costs	**High-Tech Technologies**	Advanced Oxidation Processes (AOP)	Highly effective, but energy-intensive	Very high cost, operationally intensive
Passive Treatment	Solar Water Disinfection (SODIS)	Eco-friendly, solar-powered	Very low cost, minimal maintenance	**Conventional Technologies**	Ozonation	Energy-intensive, produces no residuals	High cost, requires energy input	**High-Tech Technologies**	Granulated Activated Carbon (GAC)	Sustainable, but needs periodic replacement	Medium cost, requires periodic media replacement
Passive Treatment	Permeable Pavements	Sustainable, supports groundwater recharge	Moderate setup, long lifespan	**Conventional Technologies**	Chlorination	Chemical use, produces by-products	Low cost, but requires chemical supply	**High-Tech Technologies**	Nanoparticle-Based Disinfection	Advanced, requires specialized materials	Expensive, but very effective
Passive Treatment	Biofiltration Systems	Natural filtration, low energy	Low-cost, dependent on natural processes	**Conventional Technologies**	Engineered Wetlands	Moderate sustainability, requires land	Medium cost, requires land use	**High-Tech Technologies**	Reverse Osmosis (RO)	Highly effective, but high energy and brine waste	Very high cost, operationally expensive

Figure 3.6.4-1: List of technologies for treatment of rainwater (ChatGPT 4o).

For the treatment of rainwater from roofs the following technological steps are applied

1. Mechanical Treatment (Filtration Systems):

- Gutters and Downspouts: (First flush diverters) Installing and regularly cleaning gutters and downspouts help capture and direct rainwater while preventing debris from entering the storage system.
- Inlet Filters: Screen filters placed at the entry point of the storage system catch large debris, ensuring cleaner water collection.

2. Disinfection:

- UV Sterilizers: Ultraviolet light systems can be used to inactivate microorganisms
- Chemical Disinfection: chlorine or ozone can eliminate pathogenic organisms

3. Stabilization:

- Biological Treatment: specific bacteria into the storage tank can aid in breaking down organic matter, reducing odors, and improving water quality.

4. Photocatalytic Coatings:

- Titanium Dioxide (TiO_2) Coatings: Applying these coatings to roofing materials can facilitate the breakdown of organic pollutants on the roof surface when exposed to sunlight, thereby reducing contaminants in the collected rainwater.

5. Green roofs:

- vegetation can naturally filter rainwater, reduce runoff, and improve the quality of water collected.

The economic analysis shows that systems vary widely in cost and return on investment. Simple systems are affordable but limited in application, while complex systems—though effective and sustainable—often rely on public subsidies or long-term environmental policy goals to become viable.

3.7. Guideline for designing blue-green infrastructure for rainwater retention and groundwater recharge

Blue and green infrastructure (BGI) is one of the most important layers of sponge city. The MAURICE project developed the Catalogue of Blue Green Infrastructure Technologies (BGI catalogue) and the BGI tool to facilitate the implementation of these solutions by municipalities, designers and permitting authorities. The catalogue provides a compendium of knowledge on various BGI solutions, including detailed information on design parameters, geohazard resistance and groundwater recharge capability. The BGI tool supports the initial BGI technology by checking local inputs, precipitation scenarios, water and ground conditions, and geohazards.

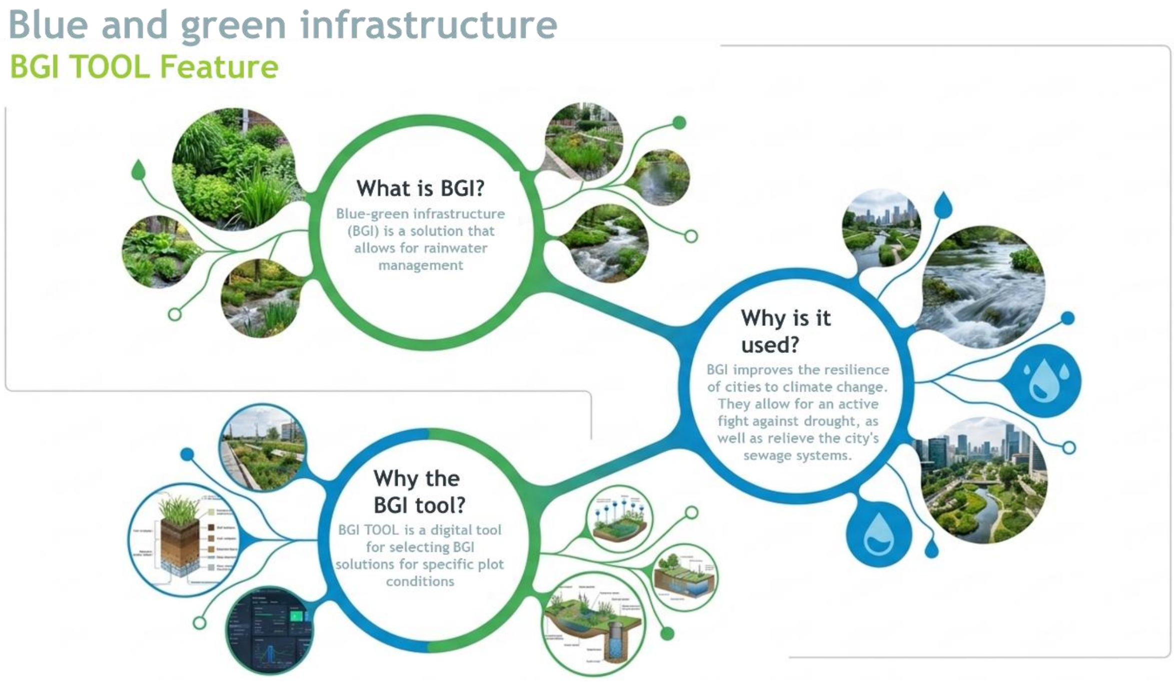


Figure 3.7-1: BGI TOOL feature.

3.7.1. Why a BGI catalogue and tool are needed

The implementation of blue-green infrastructure in practice still faces significant barriers. Investors, early concept designers, property owners and administration representatives often do not have sufficient technical knowledge to assess which BGI solutions can be used in a given location. The problem is not only the choice of technology, but also the awareness of limitations: some solutions should not be used when groundwater levels are high, with low soil permeability, unfavourable topography, or geohazards.

To address these barriers, the MAURICE project developed two complementary components designed to support the preliminary selection and assessment of blue-green infrastructure solutions. The first is the BGI Catalogue, which contains informations about available technologies with a description of functions, design parameters, design requirements, limitations of use, resistance to geohazards, retention capacity and groundwater recharge potential. The second component is the BGI Tool, which is a digital tool for the first selection of BGI technology. The tool indicates which solutions are applicable to given conditions that require caution or additional analysis, and which should be excluded. In addition, it calculates the volume of precipitation to be managed, estimates the required area for the installation and assesses the potential of groundwater recharge.

The BGI tool has been developed as a practical tool to support the early stage of investment planning. BGI Tool supports the preparation of the investment concept, the dialogue between the investor, the designer and the public administration. However, it does not replace a detailed engineering design, formal and legal procedures or specialist geotechnical and hydrogeological verification. Such analyses remain necessary at the implementation stage, especially in areas with shallow groundwater levels, historical mining activities, landslide risk, unfavorable infiltration conditions or the possibility of underground voids occurence.

Sponge city is a model of urban space management in which rainwater is harvested, infiltrated, or reused as close as possible to the precipitation site. The implementation of such an approach requires linking planning decisions with the technical assessment of the plot. The following factors are of key importance: soil permeability, groundwater table level, available area for installation, as well as geotechnical and hydrogeological risks. Special caution is required in post-industrial and post-mining areas, where the ground conditions can be strongly transformed and heterogeneous. In such areas, intensive infiltration may increase the risk of suffosion, subsidence, activation of underground voids, changes in the groundwater regime or secondary activation of pollutants. Therefore, the MAURICE approach treats BGI as a technical and natural solution: it prefers local water retention and supports groundwater recharge, but only where the groundwater conditions and the assessment of site safety allow for rainwater infiltration.

3.7.2. The BGI Catalogue: a structured knowledge base

The BGI Catalogue is designed for planners, designers, municipal officers and investors. Each technology is presented using the same logic: description of the installation, resilience to geohazards, retention capacity, potential for groundwater recharge, construction parameters, design requirements, minimum distances from sensitive objects and examples of good practice. This standardized structure makes different solutions comparable and helps users understand not only what can be built, but under what conditions it should be built.

Figure 3.7.2-1: Example catalogue card: rain garden in the ground with retention and groundwater-recharge indicators.

3.7.3. BGI Tool: decision support

BGI Tool primarily supports the early stage of investment planning It contains four operational modules.

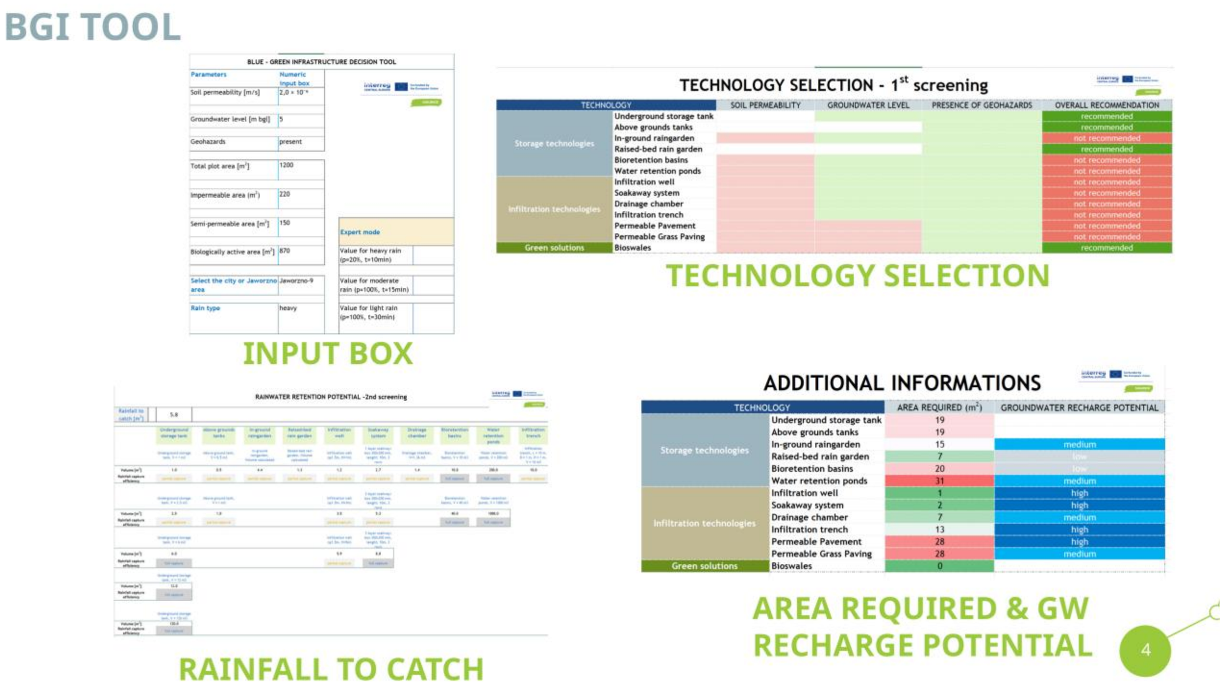


Figure 3.7.3-1: The complete BGI Tool consists of four operational modules: Input Box, Technology Selection, Rainfall to Catch, and Area Required & Groundwater Recharge Potential.

Operational modules of the BGI Tool

Module	What the user enters or receives	Decision value
Input Box	Plot area, impermeable and semi-permeable surfaces, biologically active area, soil permeability, groundwater level, geohazards, location and rainfall objective.	Converts site context into a comparable screening dataset.
Technology Selection	Automatic classification of technologies based on the local constraints.	Shows feasible, conditionally feasible and non-recommended solutions.
Rainfall to Catch	Rainfall intensity or local model values for selected rainfall objective.	Calculates the rainfall volume that should be captured or managed on site.
Area Required & GW Recharge Potential	Required footprint and qualitative groundwater-recharge potential.	Helps to verify whether the option fits the plot and supports aquifer recharge.

How the tool should be used

The BGI Tool should be used as a pre-design instrument.

3.7.4. Recommended use in municipal and investment workflows

The BGI tool is most effective when it is used early. At concept stage, it can direct the user toward measures consistent with local geology, hydrology and available space. For public administration, the BGI Tool can also create a common language between planners, environmental departments, water utilities, designers and investors.

1. Define plot	2. Check local constraints	3. Select rainfall objective	4. Compare BGI options	5. Prepare project of installation

Typical use cases include:

- screening BGI options for municipal sites, schools, sports facilities, or housing estates;
- preparing requirements for local spatial plans, development conditions or design competitions;
- supporting grant applications by providing transparent, comparable assumptions;
- communicating with residents and investors using clear visual outputs rather than expert-only calculations.

3.7.5. Pilot testing: Jaworzno permeable pavement plots

The MAURICE project in Jaworzno evaluated pilot plots with different permeable surfaces to verify whether they could be used in sponge cities.

The results of the pilot studies showed that when using permeable surfaces, surface runoff accounts for less than 5% of the water balance. In addition, the permeable surface reduced surface runoff by about 65-80% compared to the most impermeable surfaces. About 20% of the precipitation was retained and infiltrated the ground. These results confirm that permeable pavements can be a very effective BGI solution in urban areas when local conditions are appropriate and the substructure is properly designed and maintained

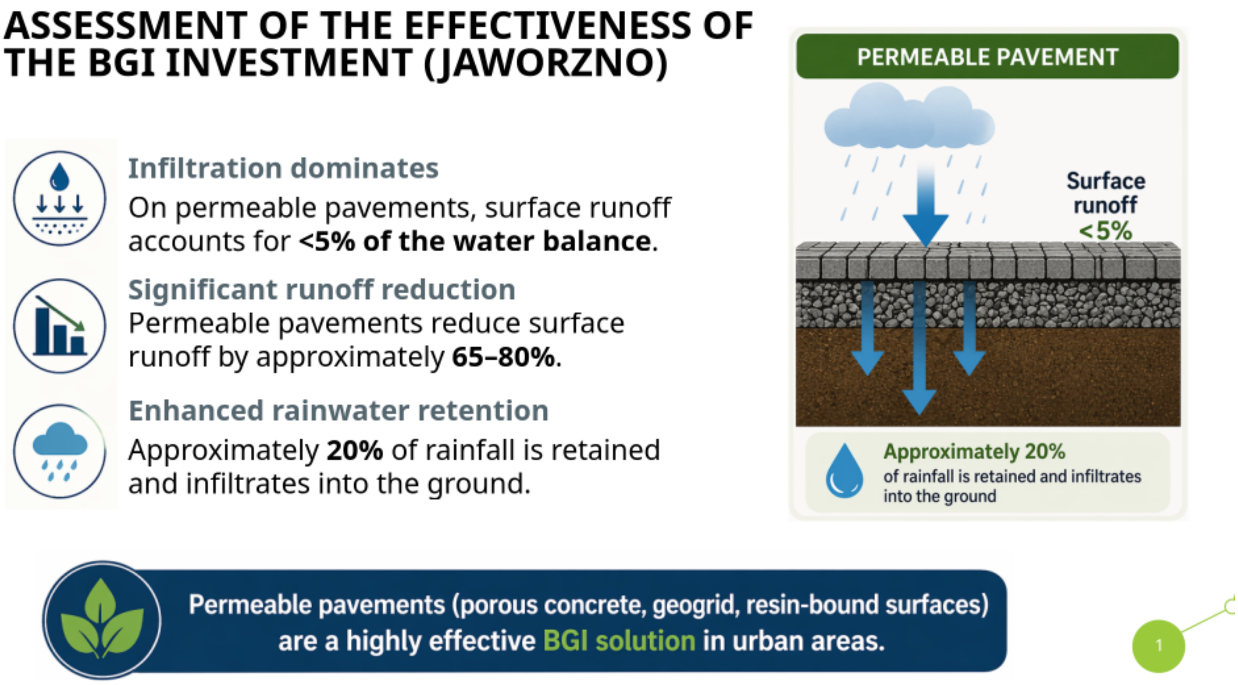


Figure 3.7.5-1: Jaworzno pilot investment results for permeable pavement BGI: infiltration-dominated performance and reduced surface runoff.

What the pilot adds to the guideline

The pilot activities showed the practical dimension of the application of BGI solutions. They are a local place for demonstration of solutions, education and workshops.

4. Added value of transnational cooperation

The MAURICE project adopted a collaborative and co-creative approach to address climate change-related challenges in urban water management across Central Europe. The transnational cooperation was structured to ensure that solutions were tailored to the specific needs of each participating city or region while leveraging shared knowledge and expertise. Hence an action plan for each of the 6 cities involved has been achieved, based on a joint management strategy.

The process was informed by pilot actions conducted in participating cities and regions, ensuring that solutions and the implementation of innovative approaches and technologies were grounded in real-world challenges and opportunities.

Figure 4-1: MAURICE Project Team.

This co-creation process is characterised by the following key elements:

- Knowledge Sharing and Capacity Building
- Integration of Local and Regional Contexts
- Use of Advanced Tools and Models
- Pilot Actions and Best Practices

This enabled the development of the partnerships' sponge city action plans in transnational cooperation.

1. **Knowledge Sharing and Capacity Building**

MAURICE leveraged existing research, technical tools, and methods from local and regional universities and external service providers. The project also built adaptive capacity by raising awareness, conducting further research, and creating supportive institutional frameworks.

2. **Integration of Local and Regional Contexts**

The project recognized that climate change impacts vary significantly based on geographical position, topography, and local climate conditions. Adaptation measures were tailored to address specific challenges, such as droughts, flooding, water scarcity, and groundwater depletion, in each region.

3. **Use of Advanced Tools and Models**

MAURICE utilized advanced climate models, conceptual and numerical models, and monitoring systems to assess risks, simulate future scenarios, and evaluate the effectiveness of adaptation measures. The project also employed the Urban Adaptation Support Tool (UAST) to guide cities and regions in developing, implementing, and monitoring adaptation plans.

4. **Pilot Actions and Best Practices**

Pilot actions were conducted in six cities (Stuttgart, Milan, Jaworzno, Novy Bydzov, Varaždin, and Ljubljana) to test and refine technical solutions for urban water management. The results of these pilots were synthesized into best practices and shared across the transnational partnership to inform the development of action plans.

5. **Development of Action Plans**

The project created detailed action plans that included specific measures, roles and responsibilities, timelines, financial plans, and monitoring concepts. These plans were designed to be binding and sustainable, ensuring long-term implementation of climate adaptation measures.