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Output 3.4.

Guideline for the selection of rainwater treatment technologies for further use

Version 2

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1. Introduction

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 NH_3 or SO_2 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, but the problem is mainly economic, it depends on several factors to choose the best cost-effective technology-based of factors such as the environment and location coupled with it's desired use. it has relatively high inputs and the return of investment depends on grants and financial support "green solution → financial aid", without financial support it wouldn´t be economically feasible on majority of the projects to even get to some return of investment, with it - it can be still as long as 15 years.

1.1. 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 advantages for some type of 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 clarify the water differently. Sometimes, a combination of two or more techniques gives the best cost-effective solution for the desired water quality level.

Emphasis is placed on pathogens transmitted by wild birds and rodents. The study of the Czech National Institute of Public Health highlights the lack of legislative requirements in the Czech Republic, the need for technical safeguards, and the danger of unintended cross-connections between potable and non-potable systems. The authors recommend a precautionary approach and continuous disinfection of the water.

Key findings:

- 40 rainwater samples were analysed.
- *Escherichia coli* was detected in 29% of samples (up to 980 CFU/100 ml).
- Enterococci were found in 53% of samples (tens to hundreds CFU/100 ml).
- *Clostridium perfringens* was repeatedly detected in some objects (up to dozens CFU/100 ml).
- No *Salmonella* or *Campylobacter* were detected (limited sampling).
- Atypical mycobacteria (*Mycobacterium gordonae*) were detected in one case.
- Water quality varied significantly based on roofing material, location, and maintenance.

https://hygiena.szu.cz/cz/artkey/hyg-202203-0002_zdravotni-rizika-pri-vyuziti-recyklovanych-vod-v-budovach-cast-1-8211-srazkove-vody.php

1.1.1. Rainwater contaminants

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

- Contaminants from materials collection sites
  - Asphalt on roads Release of polyaromatic carbons
  - Iron roofs Cu, Pb, Zn, Cd
  - Green coloured roofs = roof garden can influence the colour and turbidity of the Water

- Organic compounds and other pollutants
  - Leftovers of pesticides and herbicides from atmosphere or fields
  - Oil contamination - parking lots etc.
  - Excrements of birds and mammals

    Creation of organic contamination that supports the growth of microorganisms.

    Creation of Pathogens – Diseases

1.1.1.1. Rainwater from roofs

Main contaminants

Analyses of rainwater on roofs showed many pollutants. Main pollutants being microbial contamination which is caused by bird droppings, leaves and insects. Huge influence on water contamination has roofing materials, which are often made of metals, such as zinc or copper.[1,2,]

Influence of roofing materials

Condition and type of roofing materials could play a significant role in runoff quality. Roofs made out of metal give off increased concentrations of Zn, Pb and Cu into runoff. Of course, the age of roofs is very important as well. The older the surface on roof is, the more pollutants it releases.

Sl. no.	Location/country	Samples collected from	No. of samples analysed	Heavy metals tested	Concentrations	Salient findings	Reference
1.	Tuffeon wies, Zurich	Roof catchment	14 rain events	Cu, Zn, Pb, Cd, Cr, Mn, Fe	Concentration in µg/l in the first 0.2 mm run off depth: Cr 0.6–1.7, Fe 90–415, Pb 2.7–41, Zn 9–115, Cu 18–842, Cd 0.1–0.4	Fe and Pb exceeded quality standard in drinking water. Cu, Pb, Cd in moderately reactive forms. Gravel roof retained heavy metals	Zobrist *et al.* (2000)
2.	Marais, Paris	Roof catchment	31 rain events	Cd, Cu, Pb, Zn	Median values: Pb 392 µg/l, Zn 29 998 µg/l	High Zn and Cd concentration observed for Zn roof, and Pb for slate roof	Gromaire *et al.* (2001)
3.	Auckland, Newzealand	Water faucet	125 Samples	Zn, Cu, Pb, As	Median values: Pb <0.01 mg/l Cu 0.06 mg/l Zn 0.4 mg/l As <0.005 mg/l	14.4% samples exceeded maximum acceptable values of Pb. For Cu, Zn and As 2.4%, 0.8% and 7.1% exceeded maximum acceptable limit	Simmons *et al.* (2001)
4.	Zurich Switzerland	Roof catchment	–	Cu, Zn, Cd, Pb	Average conc. from tile and polyester roofs: Pb 16 µg/l, Cd 0.17 µg/l, Cu 225 µg/l, Zn 42 µg/l	Storm water from roof accounted for 60% Cu in combined sewer	Boller (1997)
5.	Texas, USA	Roof catchment	31 storms	Cu, Mn, Pb, Zn, Mg, Al	Median values in mg/l: A1 0.169–0.224, Mg 0.292–0.646, Mn 0.01–0.022, Cu 0.018–0.22, Pb 0.025, Zn 0.859–9.717	Cu and Zn exceeded US freshwater standards. Zn increased as rainwater contacted all four types of roofs	Chang *et al.* (2004)
6.	Austin Texas, USA	Roof catchments	12	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn	Metal concentration from different roofs: Metal Asphalt roof GI roof (µg/m^2) As 0.97–8.0 1.3–5.7 Cd 0.32–3.4 1.1–5.7 Cr 6.9–69.0 8.1–44 Cu 7–91 11–75 Hg 0.012–0.24 0.04–0.062 Ni 3.9–30 5.1–27 Pb 28–310 21–93 Zn 120–1,200 680–3,500	Metal roof tops were a source of particle-bound Zn, and Cd. As, Cr, and Cu found to be from atmospheric sources. Pb found high for asphalt roof	Metre & Mahler (2003)
7.	Maryland, USA	Roof catchment	38	Cu, Zn, Cd, Pb	Zinc concentration >100 µg/l in all samples. Mean Zn concentration from residential, commercial and institutional buildings 100, 1,100 and 1,100 µg/l respectively and Cu 7.5, 200 and 5,000 µg/l	Metal levels in institutional and commercial buildings were higher than that in residences	Davis *et al.* (2001)

Figure 1: Pollution of rainwater in different countries taken from rooftops (Meera 2006)

Setting	Parameter	Roof run-off (/100 ml)	Tank water (/100 ml)	Comments	Reference
EUROPE					
Denmark, urban area	*E. coli*		Prevalence 78.6% (*n* = 14) Range 4 – 990 Median 245	Samples taken from 7 rainwater harvesting systems	Albrechtsen (2002)
London, urban area	*E. coli*	Prevalence 94% (*n* = 88) Range 0 – 16 000 Median 52		Rainwater collected (prior to treatment) from the roof of the Millennium Dome	Birks *et al.* (2004); Birks (pers. com.)
	Enterococci	Prevalence 97% (*n* = 34) Range 0 – 680 Median >200			
England, semi rural	*E. coli*		Prevalence 34.6% (*n* = 26) Range 0 – 53	Samples taken from outside tap, possibility of mains water top-up	Day (2002)
	Faecal streptococci		Prevalence 57.7% (*n* = 26) Range 0 – 79		
Germany, urban	*E. coli*		*n* = 972 Median 26 Maximum >10 000	102 rainwater tanks	Holländer *et al.* (1996)
	Faecal streptococci		*n* = 969 Maximum > 10 000		
Scotland, rural area	Thermotolerant coliforms	Geometric mean range 383 – 3627 (*n* = 68)		Sampling from farm roofs (3 of the 4 farms were housing livestock at the time of sampling). The lowest counts were recorded from the farm without livestock.	Kay and Edwards (2003)
	Faecal streptococci	Geometric mean range 482 – 46580 (*n* = 68)			
AUSTRALIA					
Australia, rural towns	*E. coli*		Prevalence 25.5% (*n* = 47) Range 0 – 370 Mean 15		Bannister *et al.* (1997) cited by Sinclair *et al.*, 2005
Australia, urban area	Thermotolerant coliforms	Highest average figure (743) recorded at rain depths of 0.5 – 1 mm	*n* = 30 Maximum 800 Mean 119	Poor design and construction of gutters and tanks (including the installation of stormwater detention tanks rather than rainwater tanks) believed to contribute to poor water quality	Coombes *et al.* (2000, 2002)
Australia, rural, urban + industrial	Thermotolerant coliforms	Prevalence 100% (*n* = 24) Range 75 – 125	Mean counts <5 – 125	Data presented in graphical form	Thomas and Greene (1993)
Australia	*E. coli*		Not detected		Thurman (1995) cited by Sinclair *et al.* 2005
NEW ZEALAND					
New Zealand, rural area	*E. coli*		Prevalence 38% (*n* = 24) Range 0 – 111	MPN	Savill *et al.* (2001)
New Zealand, rural area	Thermotolerant coliforms		Prevalence 56% (systems) Range 0 – 840	125 rainwater harvesting systems examined, with sampling from the household tap	Simmons *et al.* (2001)
	Enterococci		Range 0 – 4900		
USA					
USA, rural area	Thermotolerant coliforms		Prevalence 3% (tanks) Typical values 10 – 20	30 tanks sampled	Lye (1987)

Figure 2 microbial pollution of rainwater in different countries taken from rooftops (Fewtrell 2007)

1.1.1.2. Surface and ground rainwater

Rainwater that is found 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.

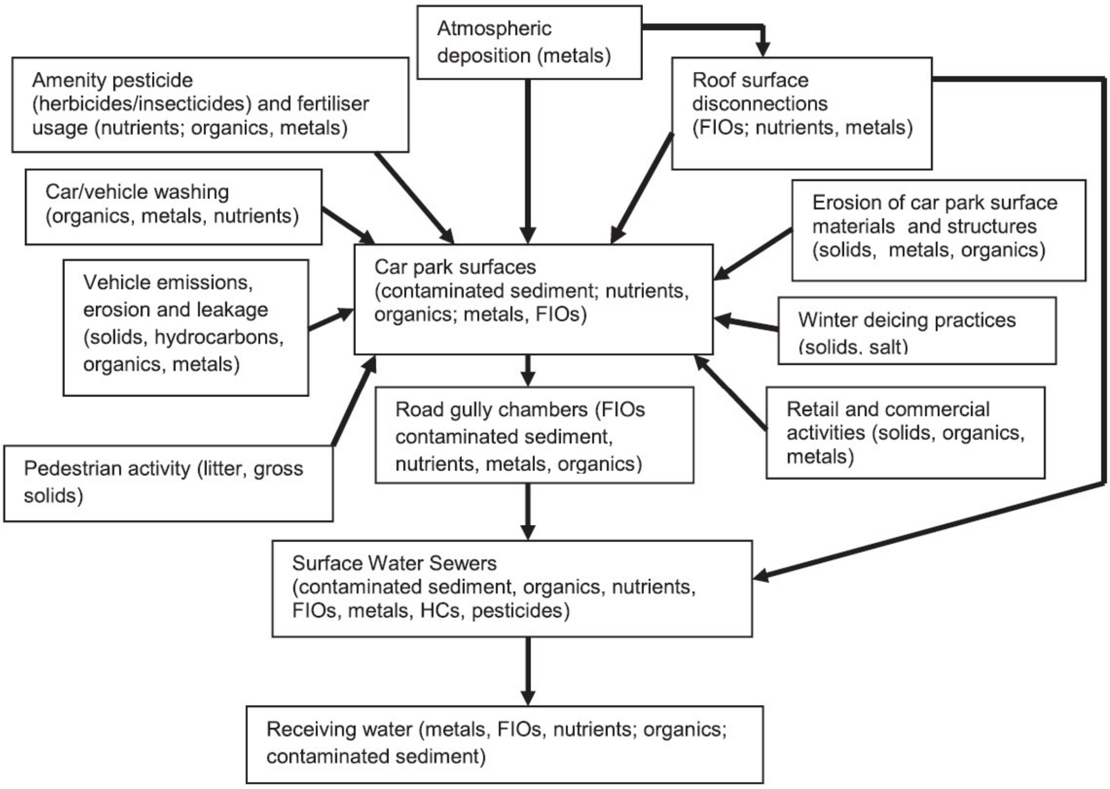


Figure 3 Principal sources and pathways of pollutants contributing to car park runoff (Lundy 2014)

The purity of rainwater is relatively high, but contamination occurs when it interacts with the surface. Water collected from roofs is mainly burdened by microbial contamination caused by organic fallout on roofs. The quality of water collected in other urban areas (roads, car parks, parks, etc.) is much lower. The main sources of contamination are traffic and human activity. It is therefore necessary to address this quality and ensure that such contaminated water does not enter the environment. In all cases, the first flush effect has a great influence on the quality. The water quality in the first minutes of rain is much lower than the water quality later.

1.1.1.3. Snow as an indicator of urban pollution

Seasonal snow covers can serve as an effective indicator of urban environmental pollution, especially in regions with cold climates. Snowflakes efficiently capture airborne particles and dissolved pollutants during precipitation, allowing the snowpack to accumulate contaminants over the winter period. Because snow samples are relatively easy to collect and represent deposition over a defined time period, they provide a useful medium for studying the spatial distribution of pollutants in urban environments (Kuoppamäki et al., 2014).

Traffic has been identified as one of the major sources of pollutants in cities, including heavy metals, nutrients and polycyclic aromatic hydrocarbons (PAHs). Studies have shown that concentrations of these contaminants in snow are significantly higher near roads and decrease rapidly with increasing distance from the roadway. The highest concentrations are typically observed within the first meters from the road, reflecting the direct influence of traffic emissions (Pilecka et al., 2019).

Pollutant accumulation in roadside snow is particularly important because during spring snowmelt these contaminants can be washed into stormwater systems and subsequently transported to surface waters. Monitoring the chemical composition of urban snow therefore provides valuable information about the intensity and spatial distribution of traffic-related pollution and helps to assess potential environmental risks associated with snowmelt runoff (Kuoppamäki et al., 2014).

1.2. Harvesting of rainwater

Designing an efficient rainwater harvesting (RWH) system starts with separating water streams based on their intended use, followed by smart pretreatment 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 RWH is locally feasible, widespread implementation in urban areas can contribute to multiple water management objectives which have **important direct benefits**:

1. Provides non-potable water source.
2. Reduces demand from distribution system.
3. Mitigates urban floods.
4. Reduces water pollution by reducing the combination of combined sewer overflows (New Directive to urban wastewater management)
5. Preserves high-quality water sources.
6. Could supply about 50% of the domestic water demand.

Non direct benefits

- Reduction in the need to upgrade water infrastructure (tap water from distribution system and sewer system)
- Energy saving and emission reduction due to reduce water abstraction, transport and treatment.

Possible use of rainwater:

1. Toilet flushing (60%)
2. Irrigation (15-20%)
3. Washing machines 20%
4. Surface washing
5. Boilers

RWH systems composition:

1. 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)
2. Roof painting without heavy metals
3. First flush diverter for the first 3-5 mm of rainfall
4. Storage tank is operated by gravity or pump (outside or underground)
5. Storage tank should contain at least 40% of runoff volume – in Czechia average storage volume should cover 21 days of consumption.

The use as Drinking water is disregarded in developer countries.

In Australia they successfully developed a good step system to build effective rainwater harvesting systems.

- Understand your rainwater needs (measurable goals: Quality and Quantity)
- Store your rainwater (underground/surface, material of vessel)
- Assess your rainwater collection area (roof, gutters, surrounding environment)
- Clean your rainwater (filter leaves and debris)
- Clean your rainwater: Divert the First Flush of rainwater.
- Secure your rainwater system (securing entry and exit points of the system)
- Decide on a pump or gravity fed system.
- Manage standing water.
- Final stage rainwater filtration / advanced treatment (reduce sediment, colour, odour before use)
- Optimise your overflow (could remove sediment from collection tank, optimum infiltration)
- Monitor your rainwater level.
- Care for your system.

https://rainharvesting.com.au

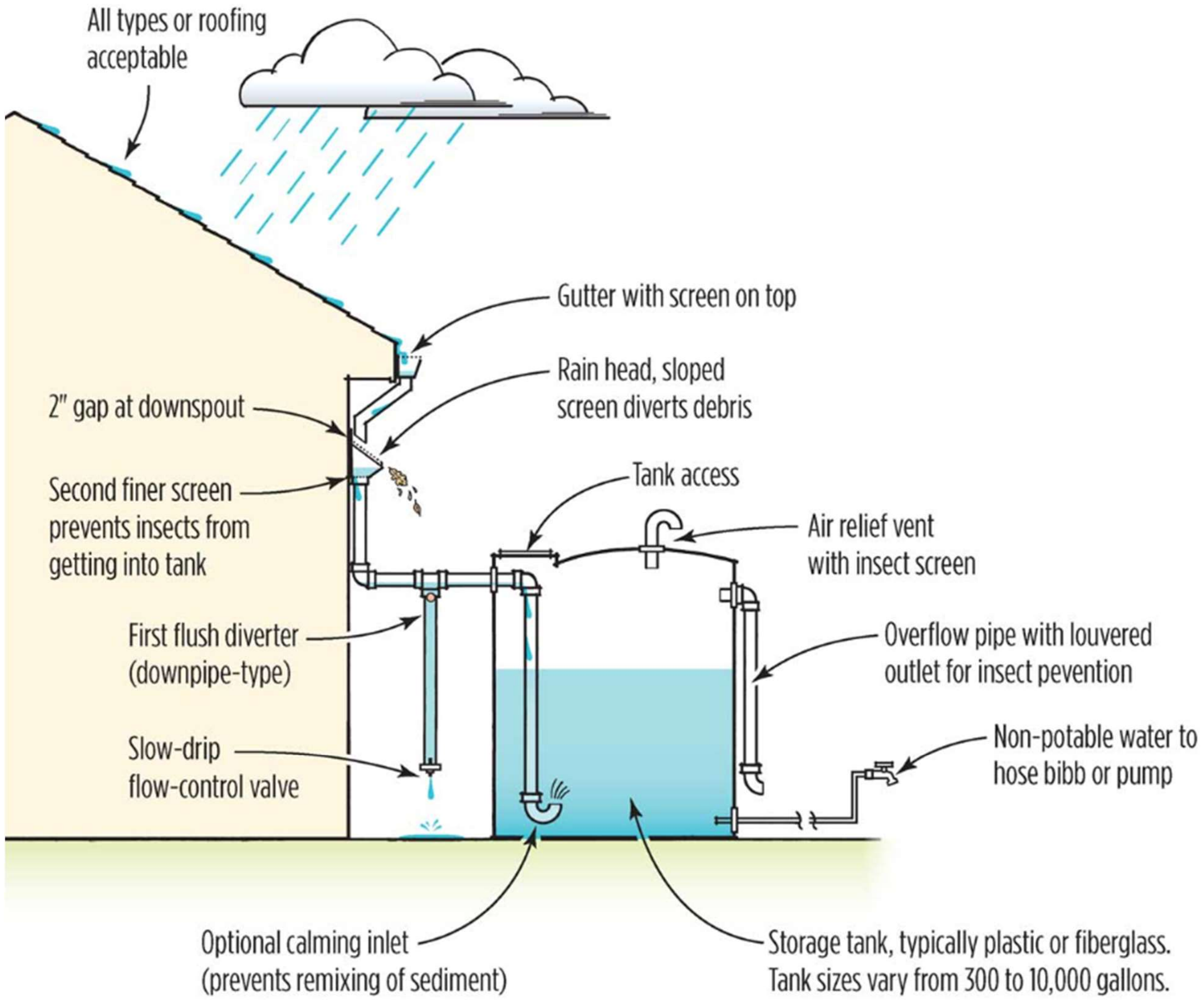


Figure 4 Rainwater harvesting diagram (energy.gov)

1.3. Treatment of rainwater

We must distinguish among the sources of rainwater, the most important are two types – those are rainwaters from roofs, and the other category is rainwater from roads, parking lots and in general from surface. 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.

1.3.1. Treatment of rainwater from ground surfaces

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.

Surfaces of transport infrastructure

- Light liquid separators - equipment designed to separate oils and other light substances from water, which is crucial when collecting water from car parks and roads.

List of technologies

- Infiltration Trenches – Low cost, prone to clogging.
- Sand Filters – Moderate cost, good for urban use, needs maintenance.
- Coagulation & Flocculation – High efficiency, chemical/sludge handling required.
- Bioretention Systems – Natural look, space-demanding.
- UV Disinfection – Chemical-free, energy-dependent.
- Activated Carbon – Broad removal, costly replacement.
- Zeolite Filters – Reusable, ion-selective.
- Granulated Ferric/Aluminum Oxides – Effective for nutrients, pH-sensitive.
- Chlorination – Cheap and effective, risk of by-products.
- Ozonation – Very effective, expensive to operate.

1.3.2. Treatment of rainwater from roofs

The following technological steps are applied in the frame of rainwater treatment.

- 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.
    - Extensive x Intensive
        - Extensive – max depth of substrate = 0.2m
            - The weight of the vegetation layer is between 80 and 300 kg/m² in the water-saturated state.
        - Intensive - max depth of substrate = 0.2 to 1.5m or more
            - The weight of a green roof can range from 300 to 2,000 kg/m².

Figure 5 Green roofs – layers (Kohler 2008)

1.3.3. List of technologies and methods

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 6 List of technologies for treatment of rainwater (ChatGPT 4o)

In EU only 1% of all systems for rainwater harvesting and treatment are using nano-membranes and advanced technologies since it is used mainly for hospitals and other place where the treatment requirement is high. The rest is mainly used for flushing toilets and for storing the rainwater into storage tanks that can be used for agriculture, garden-management, and flushing toilets, depending on the quality of the filtered and cured water it can be also used for showering.

The general water consumption is as follows:

- Potable (Drinkable) Water Need (kitchens and bathrooms): ~30–40% of total use
- Grey/Reused Water (Toilet, garden, laundry): ~60–70%

This clearly shows that even if the harvested water is not treated enough to be potable – drinkable, it can still be used for the majority of total use of water. Advanced treatment methods are typically used in facilities that produce wastewater that could pose a problem for conventional water treatment technologies or bypass them, such as antibiotics from hospitals or heavy metals from factories.

1.3.4. List of technologies and their uses

1. Conventional Systems

Description: Basic rooftop collection → gutter → storage tank (e.g. barrel or underground cistern), often without filtration.

Typical Use: Rural areas, gardens, off-grid cabins.

Uses:

- Irrigation
- Toilet flushing (manually transferred)
- Car washing

Advantages:

- Very low cost and easy to install.
- No energy needed
- DIY-friendly

Disadvantages:

- No treatment = non-potable
- Risk of contamination (debris, animals, algae)
- Limited seasonal use

Cost-Effective When: Budget is tight, and water is needed for non-potable use only.

Purpose: Simple reuse for outdoor or low-risk purposes.

2. Semi-Centralized / Intermediate Systems

Description: Rooftop collection → first-flush diverter→ sediment filter → storage tank (with pump). Partial integration into home water system.

Typical Use: Eco-homes, suburban homes with water-saving focus.

Uses:

- Toilet flushing
- Laundry
- Garden irrigation

Advantages:

- Safer and cleaner than basic systems
- Reduces mains water use by up to 40%.
- Can be automated.

Disadvantages:

- Moderate cost and some maintenance
- May require plumbing modifications.

Cost-Effective When: Municipal water is expensive, or local policies encourage reuse.

Purpose: Reliable source of greywater for household use.

3. High-Tech Systems

Description: Smart collection + real-time monitoring + multi-stage filtration (UV, carbon, membranes) → integration with household supply.

Typical Use: Smart buildings, green-certified projects, areas with water scarcity.

Uses:

- Drinking and cooking (where regulations allow)
- Full indoor and outdoor use

Advantages:

- High purity, self-regulating
- Enables near-complete water independence.
- Data logging and remote management

Disdvantages:

- High upfront and maintenance cost
- Complex installation and system management

Cost-Effective When:

- Long-term savings and water security are valued.
- In drought-prone or isolated regions

Purpose: Full-scale integration of rainwater into the home's water system.

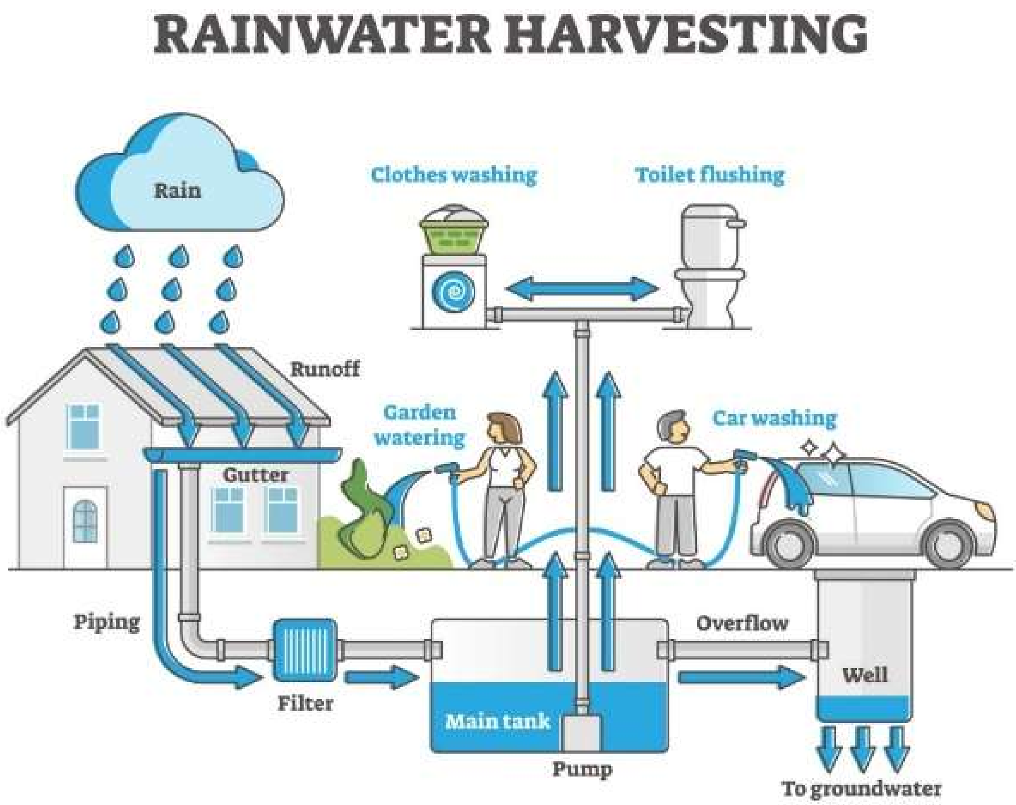


Figure 7 Rainwater harvesting diagram – conventional (allamericangutterprotection.)

1.3.5. Final sanitation and cost

Chlorination

Used primarily for stabilization and disinfection of stored or reused rainwater — especially for toilet flushing, irrigation, or street cleaning. It provides a residual effect that prevents microbial regrowth during storage and distribution.

- Hypochlorite, gaseous chlorine (water treatment, hospitals and many others)
- Chloramines (pools, agriculture)
- Chlorine dioxide (treatment of hot water distribution networks) does not form chlorinated by-products.

✔ **Advantages:** Cost-effective, simple operation, strong residual protection

✕ **Disadvantages:** Formation of disinfection by-products (trihalomethanes, trichloroacetic acid)

Figure 8 Simple operation of the chlorine dosing system for rainwater disinfection.

UV (Ultraviolet) Disinfection

Widely used for point-of-use or small-scale rainwater systems, where water is reused for toilet flushing, cleaning, or garden irrigation. It inactivates microorganisms using high-energy UV-C light, without adding chemicals.

- Short retention time: typically, 20–30 seconds.
- Easy installation and compact design.
- Operational cost: ~0.5-1 €/m^3.
- Can be combined with H_2O_2 (AOP process) to enhance removal of organic micropollutants.

✔ **Advantages:** Chemical-free process, no harmful residues, relatively easy operation, small footprint, short contact time

✕ **Disadvantages:** No residual protection after treatment, reduced efficiency in turbid water, electricity consumption (1–2 kWh/m^3)

MAURICE experience from Nový Bydžov pilot: UV disinfection was applied for the sanitation of harvested rainwater from three different buildings. Samples were stored at 12-13°C to simulate underground tanks. After 1 month, sanitation tests were carried out, and subsequent storage of sanitized rainwater (2 weeks).

Sampling	E. Coli	Coliform bacteria	Enterococci	total 22°C	total 36°C	Clostridium Perfigens
	CFU/100ml	CFU/100ml	CFU/100ml	CFU/ml	CFU/ml	CFU/100ml
3rd week of stortage						
Aquapark	0	>2000	0	>5000	>5000	0
Minkovice	0	0	0	>5000	>5000	0
Winter stadium	0	52	0	>5000	4590	0
4th week of stortage						
Aquapark	0	>5000	0	>5000	>5000	0
Minkovice	0	4	0	>5000	1850	2
Winter stadium	0	420	0	>5000	2440	2
after UV						
Aquapark	0	0	0	108	2	0
Minkovice	0	0	0	9	2	0
Winter stadium	0	0	0	820	720	0
2nd week after UV						
Aquapark	0	0	0	>5000	>5000	0
Minkovice	0	0	0	2160	1790	0
Winter stadium	0	0	0	>5000	>5000	0

Figure 9 Sanitation of stored rainwater after one month using UV irradiation followed by storage under controlled conditions.

blue-drinking water quality green - unlimited use for irrigation orange – limited irrigation (without aerosol) red – limit for any irrigation.

In-line Coagulation + Sand Filtration + Ultrafiltration

A multi-barrier process combining particle coagulation, filtration, and membrane separation. Ideal for decentralized rainwater reuse where high-quality water is required (e.g., irrigation, washing, or animal enclosures).

- Ultrafiltration with pore size < 20 nm.
- Operational cost: ~1-2 €/m³.

✔ **Advantages:** Reduces turbidity and organic matter, removes up to 99.9% of bacteria and viruses

✕ **Disadvantages:** High energy demand (especially for RO systems), membrane fouling requiring maintenance, and retentate production that must be properly treated or disposed of

TUL experience – Life4zoo project: Applied for the sanitation of a pool for tapirs in Liberec Zoo, by ultrafiltration or combined microfiltration with UV disinfection, achieving excellent microbial and physical water quality.

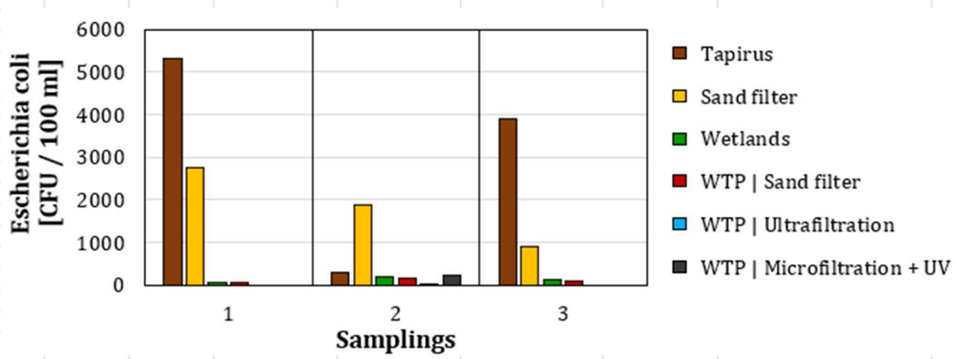


Figure 10 Results of Escherichia coli *analysis showing effective bacterial reduction after disinfection treatment.*

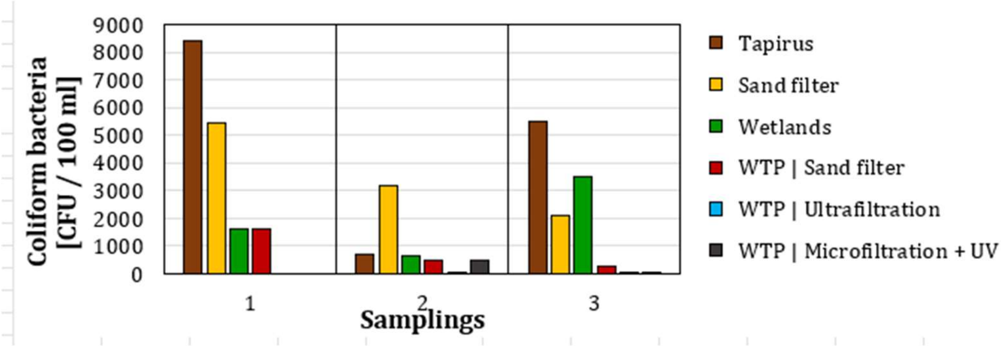


Figure 11 Results of coliform bacteria analysis showing effective bacterial reduction after disinfection treatment.

Ozonation

An advanced oxidation process suitable for centralized or large-scale rainwater reuse, where high aesthetic and hygienic quality is required (e.g., irrigation, cooling systems, or industrial reuse).

- Mechanism: O_3 acts as a strong oxidant, decomposing to reactive oxygen species (•OH) that destroy pathogens and degrade organic micropollutants
- Suitable for systems where residual disinfection is not required.

✔ **Advantages:** Effective disinfection and micropollutant oxidation; improves color, taste, and odor

✕ **Disadvantages:** High capital and operational costs (~0.3 kWh/m^3), requires durable materials and monitoring, may form harmful bromates in bromide-rich water

TUL experience: Used at the Liberec WWTP (quaternary treatment stage) primarily for micropollutant removal, but also provides effective sanitation of treated wastewater, significantly reducing bacterial counts.

Figure 12 Ozonation process applied to treated effluent from a wastewater treatment plant (WWTP Liberec, Czechia).

Sample	Concentration /contact time	E. Coli	Enterococci	total 22°C
		CFU/100ml		
13.9.				
Pilot WWTP Liberec		8 800	7 600	5 960
Ozone	0,5 mg/l	2	0	127
22.9.				
Pilot WWTP Liberec		15 600	6 200	28 800
Ozone	0,5 mg/l	2	1	12
UV irradiation + peroxide (25 mg/l)	3 seconds	22	32	16
	6 seconds	14	6	2

Figure 13 Reduction of bacterial counts achieved by ozonation at WWTP pilot unit and UV irradiation at laboratory scale.

Peroxo acids

Strong oxidants suitable for decentralized or emergency rainwater disinfection. Performic acid decomposes into formic acid, oxygen, and water, leaving no harmful residues.

✔ **Advantages:** Fast-acting, low CAPEX, minimal space requirements, environmentally friendly by-products

✕ **Disadvantages:** Higher OPEX, short shelf life, and chemical transport requirements

Plasma treatment (Caviplasma)

An emerging technology combining plasma discharge and hydrodynamic cavitation to generate reactive radicals (•OH, O_3, H_2O_2) that destroy pollutants and microorganisms.

✔ **Advantages:** No chemicals required, generates strong oxidants in situ, high efficiency in microbial inactivation, long-lasting residual effect by formation of hydrogen peroxide

✕ **Disadvantages:** High energy demand and currently limited large-scale applications.

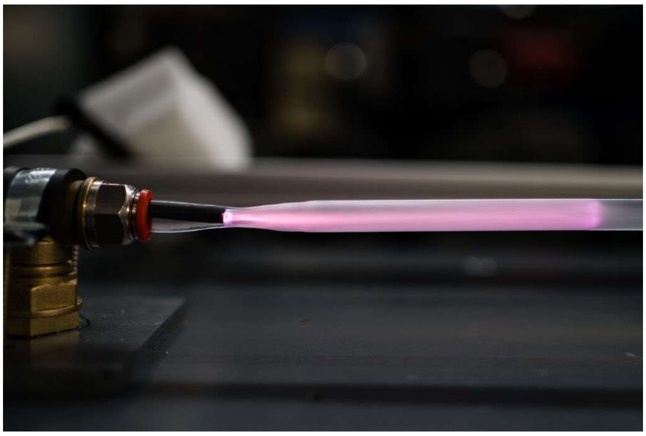


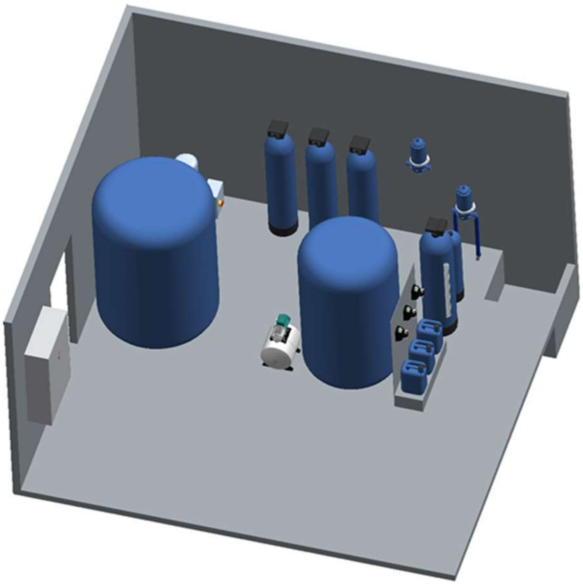
Figure 14 Plasma discharge generated by the CaviPlasma system, producing reactive species for water sanitation and micropollutant degradation.

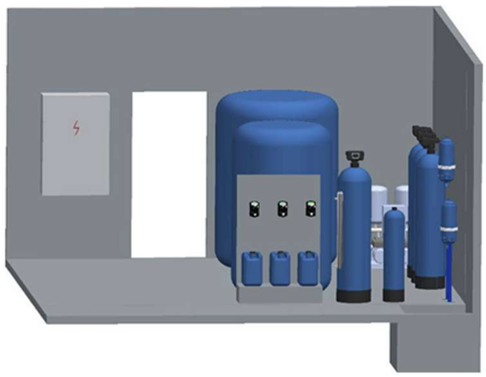
2. Economic perspective and performance, case studies

This chapter presents well-documented case studies as inspiring examples of rainwater harvesting and treatment. The first example is a design proposal developed as part of the MAURICE project for the city of Nový Bydžov. Subsequent chapters then present well-documented case studies from abroad (primarily the United States), whose significance lies primarily in the quantification of costs.

2.1. MAURICE pilot - Winter Stadium in Nový Bydžov (Czech Republic)

The utilization of rainwater at the Winter Stadium in Nový Bydžov is part of the MAURICE project. Rainwater is collected from a metal roof covering approximately 3,850 m². This system effectively minimizes potable water consumption from the public supply, thereby reducing overall operational costs. By storing rainwater in tanks and using treated groundwater from an on-site well, the facility establishes an eco-friendly, cost-effective model for maintaining the ice surface.





3D model of the pilot unit at the Winter Stadium

- **Area:** ~3850 m^2
- **System Type**: Rainwater harvesting for non-potable use.
- **Storage**: 2 steel tanks (200 m^3)
- **Treatment:**
  - Disc filter
  - Activated carbon filter.
  - UV sterilizer
  - Dosing of perchlorate bleach
  - Mixing with groundwater (Fe removal, softening)
  - Capacity 1,2 m3/h

- **Cost**: Total ~6 404 000 CZK (253 615 €) – storage tanks 122 670€, pumping pit 59 130€, Mechanical & technological part 34 550€, Mechanical electrical installation and I&C 18 450€, Additional budgetary costs 18 810€
- **Usage**: The collected and pumped water is used for filling the skating rink, preparing the ice surface, and irrigating municipal greenery.

2.2. United States and Canada

The United States has extensive experience in utilizing rainwater for various applications, and its case studies also include economic factors (both investment and operating costs). These case studies are highly inspiring, whereas there are not as many documented installations in Europe.

1. Tyson Living Learning Center (Missouri, USA)

An educational and administrative building for the Tyson Research Center (Washington University)—a 2,000-acre environmental field station dedicated to ecological research. Completed in 2009, it was one of the first buildings in the world to achieve full Living Building Challenge certification. Built on a reclaimed parking lot, the facility features net-zero energy and water systems, utilizing native landscaping (rain gardens) to manage stormwater and reduce runoff.

https://tyson.wustl.edu/living-learning-center

- **Area:** ~280 m^2
- **System Type**: Potable rainwater system with full treatment
- **Storage**: 11,360 liters underground fiberglass cistern
- **Treatment:**
    - Two sediment filters
    - Activated carbon
    - UV disinfection
    - Point-of-use bacterial filters (filters at taps)
- **Cost**: $75,000 (potable system: $60,000; non-potable system: $15,000)
- **Annual Operations & Maintenance**: ~$665

- **Usage**: All interior uses (drinking, flushing, sinks)
- **Notes**: Monthly water testing sent to the state department; cistern is chlorinated (shocked) once a year
- **Link**: https://tyson.wustl.edu/living-learning-center

2. Eco-Sense Home (British Columbia, Canada)

A multi-family "cob" residence (earthen construction) for six people, designed and built by owners Ann and Gord Baird. The home features living roofs, rainwater harvesting, composting toilets, and solar systems. It was the first internationally Petal Certified project under the Living Building Challenge. The seismically engineered load-bearing cob structure is designed to function as part of the ecosystem, emphasizing food independence and multi-generational living.

https://www.robaid.com/tech/green-architecture-eco-sense-house.htm

- **Area:** ~200 m^2
- **System Type**: Rainwater harvesting for potable and non-potable use.
- **Storage**: 37,850 liters in cisterns
- **Treatment:**
  - Green roof pre-filtration (from 185 m^2 catchment area)
  - Sequential filters: 50µm, 10µm, 1µm carbon, 0.5µm ceramic
- **Installation Costs (Hard Costs):**
  - **Potable system:** $16,000 (cistern + filtration)
  - **Non-potable system:** $16,200 (Tanks $6,700, Pumps $2,100, Filtration $2,900, Piping $2,000, Electrical $2,000, Aerator $500)
- **Annual Operations & Maintenance:** Filters $200 | Water testing $150
- **Maintenance Summary:**
  - Monthly: Clean pre-filter and flush 50-micron filter
  - Annually: Water testing, carbon media replacement, ceramic filter sterilization
- **Usage:** Potable water for all indoor household needs (drinking, cooking, bathing); non-potable water for exterior irrigation.

- **Link:** https://www.robaid.com/tech/green-architecture-eco-sense-house.htm

3. Desert Rain (Oregon, USA)

A residential compound of five structures designed for net-zero water and energy, located in Bend's high desert climate. It is the world's first Living Building Challenge certified single-family residence. The project includes a main residence, guest house, and office, all constructed with non-toxic materials and designed to mimic natural water cycles in an arid environment (receiving only ~12 inches of rain annually). It was the first permitted potable rainwater system in Oregon.

https://living-future.org/case-studies/desert-rain/

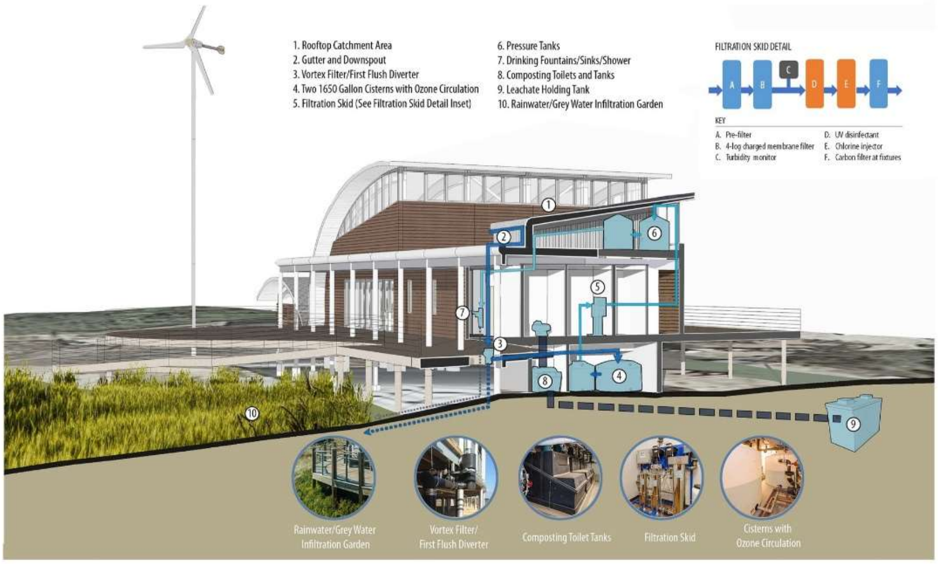
- **Area:** ~450 m^2
- **System Type**: Rainwater harvesting for full household supply (Potable)
- **Storage**: 132,500 liters from 650 m^2 roof
- **Treatment:**
  - Stainless steel gutter screen
  - Gravel filter
  - 20-micron filter (pre-cistern)
  - Two 20-micron filters (post-cistern)
  - UV disinfection
- **Cost**: $35,539 (hard costs) + $105,948 (soft costs)
- **Annual Operations & Maintenance**: ~$370 ($100 for new filters three times per year, $70 UV lamp)
- **Usage**: Full household potable supply
- **Link:** https://living-future.org/case-studies/desert-rain/

4. Brock Environmental Center (Virginia, USA)

Headquarters for the Chesapeake Bay Foundation, located at Pleasure House Point in Virginia Beach. It serves as an education, advocacy, and restoration hub and it is the first commercial building in the continental U.S. permitted to treat rainwater for potable uses. Designed for resilience, the building is raised above sea level to anticipate climate change and utilizes wind turbines and geothermal wells to achieve net-zero energy.

https://www.cbf.org/facilities/brock-environmental-center/

- **Area:** ~980 m^2
- **System Type**: Rainwater covers entire water supply (potable and non-potable)
- **Storage**: Cistern with ozone injection and attic-level pressure tank
- **Treatment**: Filtration and Disinfection
    - Multi-stage filtration (sediment, cartridge, and point-of-use filters)
    - Ozone injection
    - UV disinfection
    - Minimal chlorination (for compliance and residual safety)
    - pH adjustment via limestone contactor
- **Hard Costs**: $81,000 – total for filtration ($48,000) and tanks ($33,000)
- **Annual Operation & Maintenance**: $11,000 (includes professional waterworks operator and daily monitoring by center manager)
- **Usage**: Entire water supply needs (both potable and non-potable) of the facility
- **Link**: https://www.cbf.org/facilities/brock-environmental-center/



https://www.archdaily.com/869556/aia-selects-top-10-most-sustainable-projects-of-2017

5. Battery Park City (New York, USA)

A large urban district in Lower Manhattan serves as a model for district-scale water conservation in high-density settings. The district integrates rainwater harvesting into several buildings and public spaces as part of New York City's green infrastructure program. The district's comprehensive water reuse systems reduce wastewater discharge by over 60% compared to typical NYC buildings.

- **System Type**: Rainwater for non-potable use
- **Storage**: 30-38,000 litres
- **Treatment**: Various filtration and disinfection methods (sand, carbon, UV – depending on site)
- **Annual Operation & Maintenance**: Exact costs vary per building; systems are maintained by the Battery Park City Authority
- **Usage**: Rainwater is reused for landscape irrigation, toilet flushing, and street cleaning, reducing potable water demand in the densely populated district

6. Arch Nexus SAC (California, USA)

An adaptive reuse project in Sacramento that transformed a 1950s warehouse into a certified Living Building. This regenerative retrofit serves as a public demonstration site ("learning lab") to advocate for sustainable policy changes in California. It is designed to be net-positive for both water and energy, meeting all on-site water needs despite the region's history of drought.

https://living-future.org/case-studies/arch-nexus-sac/

- **Area:** ~770 m^2
- **System Type**: Rainwater harvesting (planned for potable and non-potable use)
- **Storage**: Two underground cisterns collecting all roof runoff
- **Treatment:**
  - Microbial filter
  - Sand filter
  - UV disinfection
- **Hard Costs**: $110,000 ($60,000 RW cisterns, $50,000 potable water treatment and storage)
- **Annual Operation & Maintenance**: Negligible, performed by in-house maintenance staff.
- **Usage**: Currently irrigation (at time of study publication). Once permitted by the State of California, it will supply sinks, showers, and dishwashers.
- **Link**: https://living-future.org/case-studies/arch-nexus-sac/

2.3. Germany

In this project, located in Berlin, rainwater infiltration was excluded from the beginning due to unfavorable soil permeability and the intensive use of limited open spaces. Instead, a rainwater collection and treatment system were implemented to supply non-potable water for residential use.

Total catchment area: 11,770 m² (63% originates from roofs, 35% from courtyards and sidewalks, and 2% from traffic surfaces)

Reservoir volume: 190 m³ (main) + 6 m³ (treated water tank)

Average treated volume: 10 m³/day

Treatment process: biological planted filter – the **upper layer** is made of expanded clay particles (8–16 mm), while the **lower layer** contains gravel (4–8 mm), separated by a 1-meter gap to ensure uniform percolation and aeration, followed by **UV disinfection** (28 W),

Supplies: 80 apartments + 6 small businesses (~200 people)

Use: toilet flushing, garden irrigation

Operation started: in 2000

Performance: stable, no clogging, consistent water quality

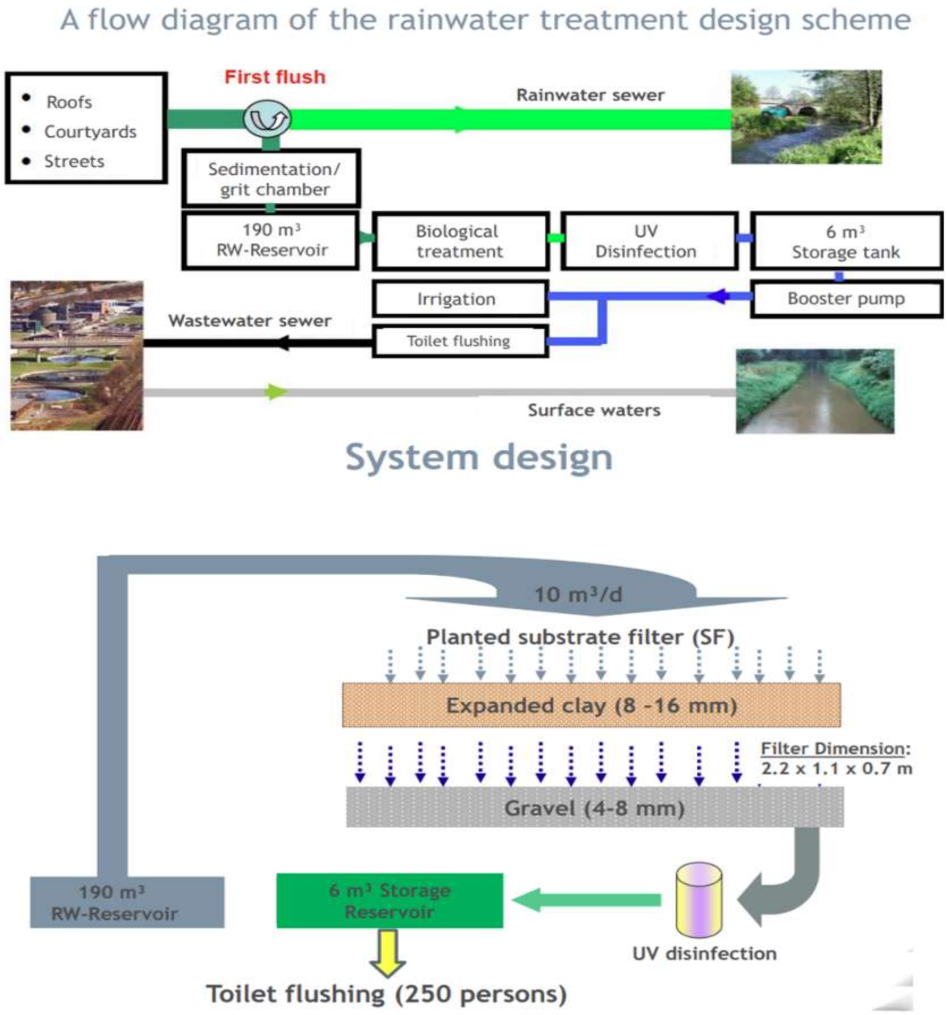


Figure 15: Rainwater treatment system in Berlin

2.4. Czech Republic

Pavilion of Tropical AgriSciences (Prague, Czechia)

The Pavilion of Tropical Agriculture is part of the Faculty of Tropical AgriSciences at the Czech University of Life Sciences in Prague. The facility serves as a research and educational centre focused on tropical and subtropical crops, integrating sustainable design principles such as green roofs and rainwater reuse. Opened in September 2020, the building replaced an older facility to improve energy efficiency and meet faculty needs. The rainwater harvesting system reduces potable water consumption and supports vegetation management around the building.

https://www.adapterraawards.cz/en/databaze/2021/pavilon-tropickeho-zemedelstvi

System Overview:

- **Catchment surfaces:**
  - **Green roof area:** ~590 m², maintained by university botanists.
  - **Surrounding landscaped areas:** Runoff is collected from the land and roof through an infiltration system.
  - **Green facades:** A metal structure on the south side supports creepers intended to shade and cool the facade.
- **Storage capacity:** 60 m³ underground tanks
- **Overflow management:** Soak-away system using four gravel-filled boreholes, enabling infiltration of excess water into the ground.
- **Water treatment:** Rainwater is filtered and mixed with tap water before distribution to ensure appropriate quality standards.

Usage: Toilet flushing, irrigation of the green roof, and climbing vegetation on facades and exterior spaces

Costs & Performance:

- **Investment cost:** 374,000,000 CZK (for the whole building)
- **Estimated ROI:** ~25 years
- **System longevity:** 25-50 years

Link: https://www.adapterraawards.cz/cs/pavilon-tropickeho-zemedelstvi

3. Conclusion

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. This document has demonstrated that although rainwater is relatively clean in its atmospheric form, significant contamination occurs upon contact with surfaces such as roofs and urban ground areas. Therefore, the quality of collected rainwater is highly dependent on catchment material, environmental conditions, and maintenance practices.

The treatment of rainwater must be tailored to its intended use—non-potable uses like toilet flushing, irrigation, and washing require less intensive treatment, while potable uses demand multi-stage, often high-tech solutions. Technological approaches range from conventional systems (basic tanks and screens) through semi-centralized setups (with filtration and pumps) to advanced systems with membranes, UV, and real-time monitoring. Notably, green roofs and pre-filtration techniques like first-flush diverters play a key role in improving initial water quality before treatment even begins.

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. In the EU, less than 1% of systems use nano-membranes or advanced purification, underscoring a strong focus on cost-effective, non-potable reuse. Real-life examples from the U.S., Canada, and Czech Republic illustrate how system design, investment, and functionality vary based on local conditions, regulation, and ambition.

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. Where legislation lags behind, precautionary design and consistent disinfection are recommended.

4. Resources

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