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GAIN project: Impact of infiltration of rainwater from potentially contaminated surfaces on groundwater quantity and quality

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GAIN project: Impact of infiltration of rainwater from potentially contaminated surfaces on groundwater quantity and quality

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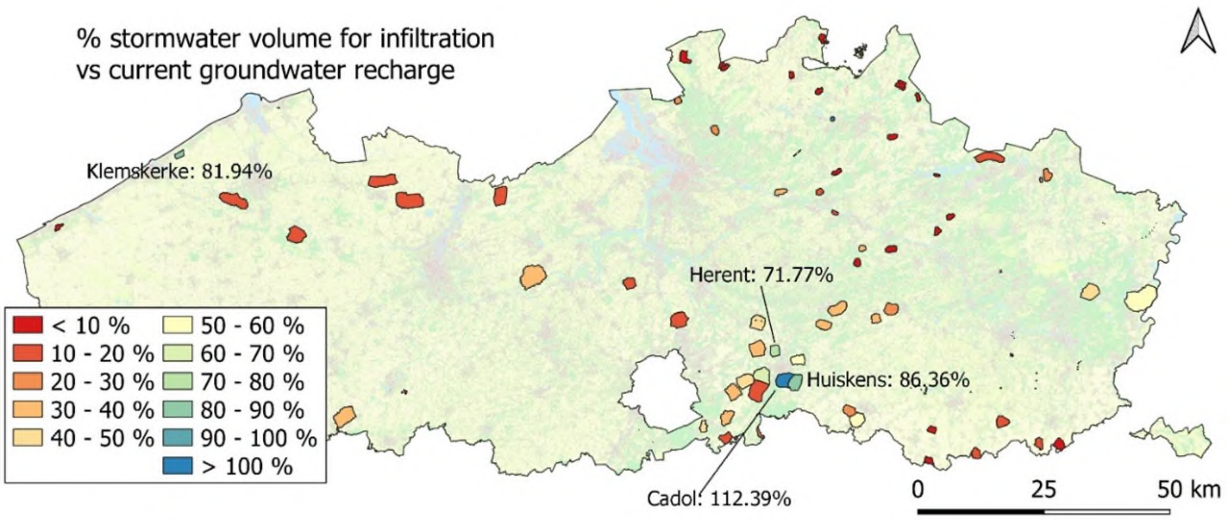
Managementsamenvatting

Terughoudendheid aanbevolen met infiltratie regenwater van potentieel verontreinigde oppervlakken in verband met mogelijke effecten op grond- en drinkwaterkwaliteit

Auteurs: Lara Speijer, Bas van der Grift, Gijsbert Cirkel, Marijke Huysmans.

Vlaanderen kent veel verharde oppervlaktes als daken, wegen en parkings. Afstromend hemelwater van deze verharde oppervlaktes vormt een interessante bron voor infiltratie en grondwateraanvulling in Vlaanderen. De Vlaamse regelgeving moedigt maatregelen voor verhoogde infiltratie aan om de ondergrond als buffer tegen zowel droogte als overstromingen te gebruiken. De opheffing van het infiltratieverbod in beschermingszones van grondwaterwinningen voor drinkwaterproductie leidt echter tot bezorgdheid over de (grond)waterkwaliteit. Een GIS-analyse en literatuuronderzoek naar de kwaliteit en impact van hemelwater op het grondwater toont een hoog potentieel voor grondwateraanvulling met regenwater in Vlaamse beschermingszones. De lokale verschillen zijn groot, met een maximum rond Leuven. Recente metingen geven echter aanleiding tot bezorgdheid over het voorkomen van tientallen organische microverontreinigingen in afstromend hemelwater. Over hun voorkomen en concentraties in Vlaams en Nederlands afstromend regenwater is nog onvoldoende bekend. Ook ontbreekt het nog aan voldoende inzicht in de natuurlijke zuiveringscapaciteit van bodems om het werkelijke risico van grondwater-verontreiniging te duiden, vooral voor geladen organische verbindingen. Terughoudend zijn met grootschalige infiltratie van ongezuiverd hemelwater in beschermingszones van grondwaterwinningen is daarom aanbevolen.



Potentieel van extra grondwateraanvulling door hemelwaterinfiltratie vanaf verharde oppervlakken ten opzichte van de huidige aanvulling binnen Vlaamse grondwaterbeschermingsgebieden

Belang: infiltratie met potentieel verontreinigd regenwater kan grondwaterkwaliteit beïnvloeden
De droge zomers van afgelopen jaren hebben duidelijk gemaakt dat Vlaanderen moet inzetten op droogteadaptatie. Opgevangen hemelwater vormt een interessante alternatieve bron voor het aanvullen van grondwater wereldwijd. Gegeven het hoge percentage verhard oppervlak is er een groot potentieel voor deze maatregel in Vlaanderen. Regelgeving, waaronder de Blue Deal, zet daarom in op infiltratie en het verhogen van de grondwatervoeding. Als gevolg hiervan is het infiltratieverbod in beschermingszones van drinkwaterwinningen opgeheven. Afstromend

hemelwater kan echter verontreinigingen bevatten wat mogelijk een risico vormt voor de grond- en drinkwaterkwaliteit.

Aanpak: GIS-analyse en literatuurstudie
De eerste fase van het GAIN (Grondwaterkwaliteit Afstromend regenwater INfiltratie) project focust op kwantiteits- en kwaliteitsaspecten van grondwater bij infiltratie van stedelijk afstromend hemelwater. Een GIS-analyse is uitgevoerd om een eerste indruk te krijgen van het mogelijke potentieel van hemelwaterinfiltratie voor het aanvullen van het grondwater in Vlaamse beschermingszones. Hemelwatervolumes zijn berekend op basis van het oppervlak aan verharde oppervlaktes, de jaarlijkse neerslag in Vlaanderen en een afstromingscoëfficiënt om rekening te houden met verliezen als verdamping. Om de significantie van deze hemelwatervolumes te bepalen zijn deze vergeleken met de huidige grondwatervoeding en opgepompte volumes uit de freatische aquifers. Vervolgens is een literatuurstudie uitgevoerd naar de kwaliteit van afstromend hemelwater op internationaal, Nederlands en Belgisch niveau, met een specifieke focus op organische microverontreinigingen. Daarbij is ook literatuur geanalyseerd over de zuiverende werking van bodempassage op het infiltratiewater.

Resultaten: hoog potentieel voor aanvulling, onvoldoende zicht op organische micro's
De resultaten tonen een hoog potentieel voor infiltratie van afstromend hemelwater in Vlaamse beschermingszones, met een gemiddelde van 29% extra grondwatervoeding door hemelwaterinfiltratie. Bij infiltratie van al het afstromende regenwater kan de extra voeding oplopen tot 33% van het door een winning opgepompte jaarvolume. Grote lokale verschillen zijn echter merkbaar, met het hoogste potentieel in beschermingszones rond Leuven. Uit de literatuurstudie blijkt dat de focus ten aanzien van kwaliteitsaspecten vooral heeft gelegen op 'klassieke' verontreinigen zoals zware metalen en PAKs. Deze verontreinigingen binden zich doorgaans vrij gemakkelijk aan sedimentdeeltjes of breken goed af in de bodem, waardoor het risico op grondwaterverontreiniging voor deze stoffen relatief beheersbaar is. Uit recente onderzoeken in onder andere Frankrijk en Duitsland blijkt echter dat naast deze verontreinigen een groot aantal andere organische microverontreinigingen in afstromend hemelwater wordt aangetroffen. In deze studies zijn tientallen verontreinigingen aangetroffen, waaronder bestrijdingsmiddelen en industriële stoffen als PFAS, benzotriazolen, HBCD en PBDE. Deze stoffen zijn afkomstig van onder andere autoverkeer, bouwmaterialen en het gebruik van bestrijdingsmiddelen in de landbouw en in de openbare ruimte. Deze stoffen kunnen mobiel en persistent zijn in de ondergrond en vormen daarmee mogelijk een risico voor de drinkwaterkwaliteit. Momenteel bestaat er nog onvoldoende inzicht in de aanwezigheid van deze stoffen in Nederlands en Vlaams afstromend hemelwater om het risico afdoende te duiden. Daarnaast is het niet duidelijk in hoeverre deze stoffen uit het hemelwater worden verwijderd tijdens infiltratie en transport in de bodem. Hiervoor is aanvullend onderzoek nodig naar het verwijderingsrendement en de biogeochemische mechanismes hierachter.

Implementatie: terughoudend zijn met infiltratie in beschermingszones drinkwaterproductie
Infiltratie van hemelwater heeft een hoog kwantitatief potentieel bij Vlaamse grondwaterwinningen. Er is echter nog onvoldoende bekend over het voorkomen en de concentraties van (micro)verontreinigingen in afstromend hemelwater in Vlaanderen en Nederland. Ook ontbreekt voldoende inzicht in de natuurlijke zuiverings-capaciteit van bodems om het werkelijke risico te duiden, vooral van geladen organische verbindingen. Terughoudendheid met grootschalige infiltratie van ongezuiverd hemelwater in beschermingszones van grondwaterwinningen is daarom aangeraden.

Rapport
Dit onderzoek staat beschreven in het rapport *GAIN project: Impact of infiltration of rainwater from potentially contaminated surfaces on groundwater quantity and quality* (BTO 2023.091).

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Contents

1 Introduction

1.1 Problem statement

Extreme weather events such as droughts and floods are expected to increase in Flanders (Belgium) due to climate change. Climate models predict a decrease in summer precipitation and an increase in winter precipitation (Tabari et al., 2015; Vlaamse Overheid, 2022a). As a consequence of recent dry summers in 2018, 2019, 2020, and 2022, phreatic groundwater levels have been very low for the time of the year in the majority of observation points (VMM, 2022). Additionally, water stress in the region is pressing due to a high population density, water-intensive economic activities, and a history of drainage practices (Vlaamse Overheid, 2022a). To enhance resilience against drought and water scarcity, Flanders promotes infiltration measures through the Blue Deal, a policy plan to tackle drought and water scarcity (Integraal Waterbeleid, 2020). Globally, stormwater harvested from impermeable surfaces is seen as a valuable alternative water source for Managed Aquifer Recharge (MAR) (Angrill et al., 2017; Dillon et al., 2014). Given the high urbanization level and percentage of sealed surfaces (16%) in Flanders (Vlaamse Overheid, 2022a), large volumes of stormwater could potentially be harvested and infiltrated to enhance groundwater recharge in the area.

However, the use of stormwater for MAR applications may be associated with water quality risks. Depending on the type of impermeable surface, stormwater can contain contaminants that threaten groundwater quality and could clog the infiltration system. Important contaminants include nutrients, inorganic compounds (i.e. metals and ions), organic compounds, PAH, and pathogens, but their presence in stormwater varies widely (Angrill et al., 2017; Bekele et al., 2018; Fairbairn et al., 2018; Song et al., 2019). Less is known about micropollutants and emerging contaminants in stormwater such as pesticides, and PFAS (Fairbairn et al., 2018; Pinasseau et al., 2020; Saifur & Gardner, 2021; Sánchez et al., 2015). For example, pesticides which are banned for use as a herbicide can be present in rooftop stormwater due to their usage in construction as biocides and insecticides that are banned in agriculture are widely used for treatment of domestic animals against ticks and fleas. Stormwater micropollutant concentration measurements are however very limited, but scarce measurements are cause for concern (De Buyck et al., 2021; Sánchez et al., 2015).

Historically, stormwater infiltration in protection zones around Flemish groundwater abstraction wells for drinking water production has been prohibited to prevent groundwater contamination. However, given the increased focus on infiltration and drought adaptation measures to counter water scarcity risks, new policy guidelines have removed this infiltration ban (Vlaamse Overheid, 2013, 2023), raising the concern of potential groundwater quality deterioration. To decide on infiltration policies or specific infiltration projects in drinking water protection zones, drinking water companies and policymakers need tools to assess the impact on groundwater quantity and quality. In this way, they can balance the significance of such measures for reducing water scarcity relative to the potential risk of groundwater quality deterioration. In this study (phase 1) we provide a first insight in the significance of infiltration measures in abstraction zones and water quality considerations with respect to the presence of emerging contaminants in stormwater.

1.2 Research questions and objectives

This report stipulates the results obtained in the first phase of the GAIN (Grondwaterkwaliteit Afstromend regenwater INfiltratie) project. The GAIN project's overall goal is to investigate whether the quantitative gains of stormwater infiltration can outweigh potential water quality impacts on groundwater resources in Flemish drinking water production zones. The aim of this first phase was to gain a first insight into the potential of stormwater infiltration for aquifer recharge based on desktop research. Firstly, this includes an investigation of the potential quantitative impacts of stormwater infiltration to enhance groundwater recharge based on a GIS analysis. This GIS analysis quantifies the stormwater potential from impermeable surfaces including roofs, roads and parking lots for aquifer recharge enhancement in Flemish protection zones. Secondly, a first assessment of the water quality considerations of stormwater infiltration has been carried out based on a review of international and Dutch and Belgian literature with a special focus on organic micro pollutants in runoff from buildings and roads.

2 GIS-analysis on the potential impact of stormwater infiltration on groundwater quantity

In order to balance the quantitative benefits and qualitative risks from increased stormwater infiltration for groundwater resources, it is essential to assess if increased infiltration can significantly increase groundwater recharge. Therefore, a GIS analysis was carried out to quantify the potential impact of stormwater infiltration on the groundwater system in Flemish groundwater protection zones. This section is predominantly based on Speijer et al. (2024, in review).

2.1 Introduction

In order to quantify the potential of stormwater infiltration to increase groundwater recharge, it is essential to firstly quantify available stormwater volumes in the study area. Rainwater harvesting volumes are in literature commonly calculated by multiplying the impermeable surface area with the precipitation over this area. Additionally, this volume is multiplied by a runoff coefficient to account for processes such as evaporation, seepage through degraded materials, and initial surface wetting (Angrill et al., 2017; Farreny et al., 2011). Farreny et al. (2011) quantified roof runoff coefficients varying between 0.62 for flat gravel materials and > 0.9 for sloping, smooth materials (e.g. metal or plastic roofs). Similarly, Angrill et al. (2017) calculated runoff coefficients between 0.41 and 0.89 for road surfaces (e.g., asphalt or concrete material on roads, parking lots, pedestrian areas). Furthermore, studies investigating the impacts of stormwater infiltration on groundwater often use modelling tools to investigate the impacts on groundwater recharge, groundwater levels, and transport processes (Clark et al., 2015; Ringleb et al., 2016). For example, Russo et al. (2015) investigated the impact of suitable MAR locations in the Pajaro Valley in California on groundwater levels and concluded that MAR projects would reduce seawater intrusion. Alam et al. (2021) estimated a potential compensation of the groundwater withdrawal in California by MAR applications of up to 22% based on a coupled surface water-groundwater model.

However, such modelling efforts require an extensive investigation of the study site. These methods are suitable for quantifying the impacts of specific infiltration sites but are not feasible at a regional or national scale to assess the cumulative potential of stormwater infiltration or identify high-potential regions. Therefore, this research proposes a novel approach based on a GIS analysis to quantify the stormwater potential for aquifer recharge enhancement, using meteorological data, land cover, groundwater recharge, and abstraction data. The approach allows calculating the impact of the following what-if scenario: “What if all stormwater from impermeable surfaces in protection zones would be infiltrated instead of discharged into the sewer system?” The analysis can be used as a screening methodology to assess which areas have the most stormwater potential for groundwater recharge. The additional groundwater recharge due to infiltration with stormwater originating from impermeable surfaces is compared to current groundwater recharge and pumping rates in protection zones to assess its potential relevance and to answer the question: “What are the potential impacts of stormwater infiltration on groundwater recharge volumes in groundwater protection zones in Flanders?”.

2.2 Materials & methods

2.2.1 GIS methodology

A quantification of stormwater infiltration potential for enhancement of groundwater recharge was carried out through a GIS analysis of impermeable land cover types in the protection zones around groundwater wells in Flanders. This analysis was carried out with QGIS (version 3.22.11) and Python (version 3.9.16). Table 1 provides a summary of used input data for this methodology.

Table 1: Data needed for the GIS methodology to quantify the stormwater infiltration potential in Flemish groundwater protection zones

Type of data needed	Specifications of used data for Flanders
Land cover map with indication of impermeable or urban surfaces	Flemish land cover map, 1 x 1 m, 14 land cover types, including 4 urban land cover types (i.e., buildings, roads, other sealed, railways) (Agentschap Digitaal Vlaanderen, 2018)
Drinking water protection zones map	Flemish drinking water protection zones map (Vlaamse Overheid, 2022b)
Precipitation data	Average yearly precipitation rate in Uccle, Brussels (1990 – 2020) (Vlaamse Milieumaatschappij, 2023)
Groundwater recharge map	Annual groundwater recharge map of Flanders based on WETSPASS model outputs, 50 x 50 m (Zomlot et al., 2015)
Pumping rates for drinking water production	Maximum yearly pumping volume in 2016-2020 for phreatic drinking water wells of De Watergroep

The Flemish land cover map (Agentschap Digitaal Vlaanderen, 2018) with a resolution of 1 by 1 m consists of fourteen land cover types. Four land cover types were identified as urban, impermeable land cover types: 'buildings', 'roads', 'other sealed' (e.g., parking lots), and 'railways'. This map was overlain by Flemish drinking water protection zones (Vlaamse Overheid, 2022b) to quantify the total impermeable surface area in groundwater protection zones, by using the 'zonal histogram' QGIS tool. Several drinking water companies are active in Flanders, of which De Watergroep and Pidpa (active in the province of Antwerp with wells mainly in the Campine region) possess the majority of wells in Flemish groundwater protection zones. Results in this paper stipulate calculations for the complete protection zone (zones 1, 2, and 3 merged). Then, percentages of land cover types per protection zone were calculated in Python. Next, an average yearly precipitation rate of 836 mm/year (Uccle, 1990 – 2020) (Vlaamse Milieumaatschappij, 2023) was assumed to fall on all impermeable surfaces. Spatial variations of precipitation rates in Flanders are minor and assumed to be negligible for this analysis (Koninklijk Meteorologisch Instituut van België, 2023). A slight annual increase in precipitation rate of + 0.55 mm/year in Flanders is noticeable (VMM Dienst Mira, 2015), indicating that these calculated stormwater volumes may slightly increase in the future. Furthermore, this total volume of precipitation on impermeable surface types is multiplied by an average runoff coefficient of 0.75, based on roof and road runoff coefficients established by Farreny et al. (2011) and Angrill et al. (2017), to account for evaporation, initial wetting and seepage through cracks of the sealed surfaces.

To put the calculated stormwater volumes into perspective, a comparison was made with two types of data to assess the significance of stormwater infiltration for extra groundwater recharge in Flemish protection zones. First, potential stormwater volumes were compared with the current groundwater recharge map of Flanders, simulated in the WETSPASS model (50 x 50 m) by Zomlot et al. (2015). Important sidenote is the uncertainty related to groundwater recharge estimations in general (Scanlon et al., 2002), and especially with regards to future climate change projections (Reinecke et al., 2021). Uncertainties in groundwater recharge calculations in WETSPASS are addressed by Batelaan & De Smedt (2007), and include uncertainties from model conceptualization, measurement errors and input uncertainties such as land cover, precipitation… The groundwater recharge map of Flanders (Zomlot et al., 2015) was converted from mm/year to m³/year to obtain the volume of groundwater recharge in each pixel, whereafter the 'zonal statistics' QGIS tool calculated the sum of groundwater recharge of all pixels in a protection zone. The comparison with stormwater volumes was established through a Python script calculating the percentage of potential additional stormwater volume compared to current natural groundwater recharge.

Likewise, a second comparison was made with total pumping volumes for drinking water production in the protection zones of De Watergroep (i.e. 25 protection zones), Flanders' biggest drinking water company (De Watergroep, n.d.). Other protection zones were not taken into account since no data was available for the other groundwater wells. Only phreatic wells were included, as infiltration will have the most quantitative and qualitative impacts on shallow, phreatic aquifers (De Vries & Simmers, 2002; Machiwal et al., 2018; Simmers, 1997). First, an assessment was made on which pumping wells are located in which protection zone. The maximum yearly pumping volume in the period 2016-2020 was taken, and the sum of all pumping volumes in one protection zone was calculated to obtain the total maximum pumping volume in each protection zone. Then, the comparison with stormwater volumes was established for each groundwater protection zone by calculating the percentage of stormwater volume (i.e. extra potential water volume for groundwater recharge) compared to simulated current groundwater recharge and the summarized pumping volumes. Therefore, this analysis assesses the theoretic potential of stormwater infiltration measures to compensate groundwater well pumping volumes.

2.2.2 Limitations

A few assumptions were made in order to carry out this GIS analysis. An average runoff coefficient for stormwater from roofs and roads based on Angrill et al. (2017) and Farreny et al. (2011) was applied, as the available land cover map is not suitable to distinguish the types of roofing and road materials (e.g., concrete or asphalted roads, and clay tiled or metal roofs). Taking the different surface types and associated runoff coefficients (Angrill et al., 2017; Farreny et al., 2011) into account would improve the accuracy of this analysis. Furthermore, estimates indicate that around 50% of Flemish households possess a rainwater tank, given the obligation to install a rainwater tank in new and renovated buildings since 2013 (Vlaamse Overheid, 2013, 2021). Although this stimulates household water reuse for purposes such as toilet flushing and gardening, this also implies that the maximum stormwater volume for infiltration will be reduced. Nonetheless, these rainwater tanks have a certain limited capacity, and the use of an infiltration facility for the overflow is strongly encouraged (Vlaamse Overheid, 2023). Lastly, all urban surfaces (i.e., roads, roofs, railways, and other sealed surfaces such as parking lots) are assumed to be completely impermeable. However, it is possible that some roads have been made semi-impermeable, or roadside infiltration exists. The conversion of impermeable to (semi-)impermeable surfaces is encouraged in Flemish regulations (Integraal Waterbeleid, 2020). Given these assumptions, it is clear that these calculated stormwater volumes and extra groundwater recharge potentials have to be seen as maximum potential in case all generated stormwater would recharge the groundwater system.
A second limitation of this analysis is related to the comparison with pumping volumes. This GIS analysis does not take into account principles of groundwater dynamics, including hydrogeology and drawdown at pumping wells (Fitts, 2013). Therefore, this methodology only focuses on comparing stormwater and pumping volumes, and does not have the intention to propose conclusions on the effects on groundwater levels. To take this into account and to assess flow paths and residence times of the infiltrated water, future research is needed that assesses the impacts of infiltration measures on groundwater heads, using groundwater modelling as a tool to incorporate principles of groundwater flow (Ringleb et al., 2016).

2.3 Results and discussion

2.3.1 Stormwater volumes in protection zones

Land cover types in the protection zones were analysed to gain a first insight into the amount of impermeable surfaces and associated stormwater runoff volumes. Figure 1 and Figure 3 show that a significant fraction (11.97% on average) of the protection zones consists of impermeable surfaces due to urban land cover types including buildings, roads, railways, and other sealed surfaces such as parking spaces. This is in line with the high urbanization degree and imperviousness percentage (16%) in Flanders (De Decker, 2011; Poelmans & Van Rompaey, 2009; Statbel, 2022; Vlaamse Overheid, 2022a). However, large variations in the fraction of urban land cover types in protection zones are noticeable (0 to 68.58%). This is largely related to the amount of built-up area in these zones. For example, it is specifically noticeable that protection zones in the Campine area have smaller percentages of impermeable surfaces, given the lower population density in the area (352 inhabitants/km² in 2018) (Streekplatform Kempen, 2018). Similarly, protection zones east of Brussels are located close to the city of Leuven. This is a university city and province capital with a little over 100 000 inhabitants (Stad Leuven, 2023), excluding the student population, leading to protection zones located in urbanized, densely populated areas. A further investigation into the different types of urban land covers (Figure 2 and Figure 3) shows that many protection zones have an approximately equal contribution of 'buildings', 'roads', and 'other sealed surfaces', with an average of around 3-4% of the total protection zone each. The only exception is the land cover type 'railways' which takes nearly negligible space in the protection zones.

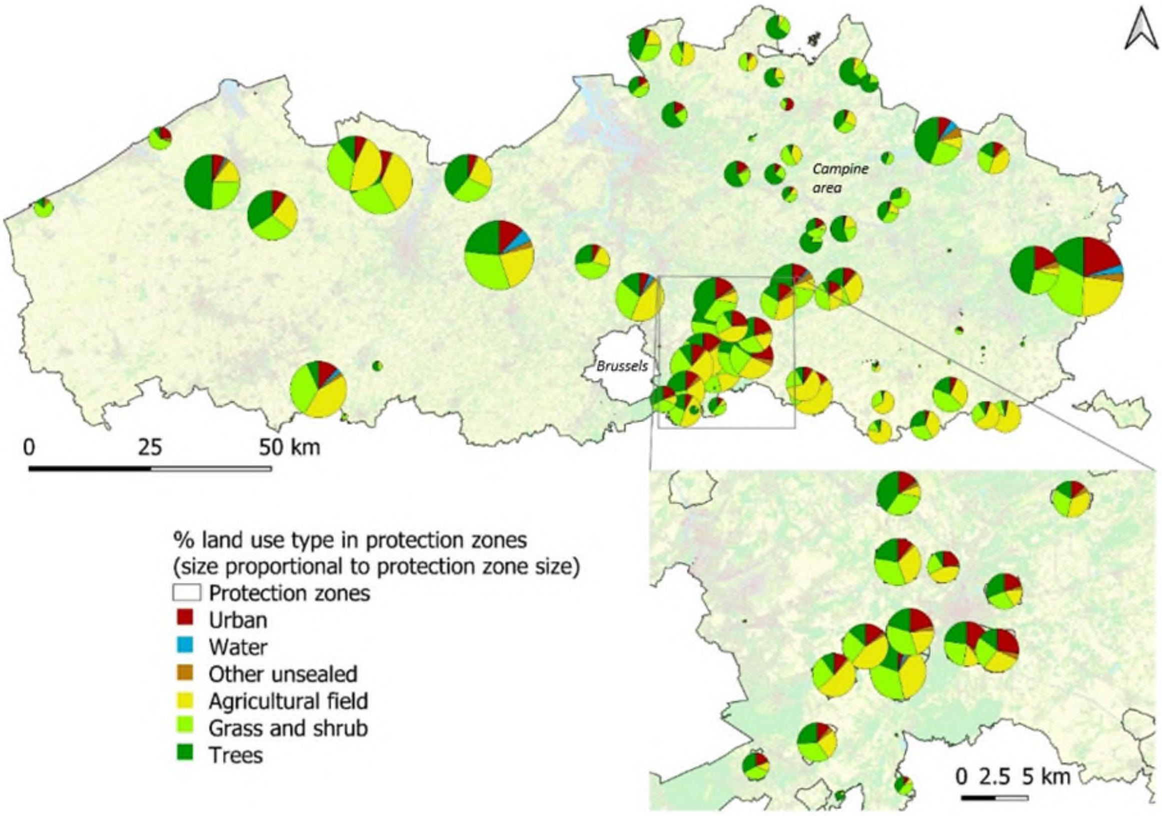

Figure 1: Distribution of major land cover types in protection zones, based on data from Agentschap Digitaal Vlaanderen (2018) (sizes relative to protection zone size)

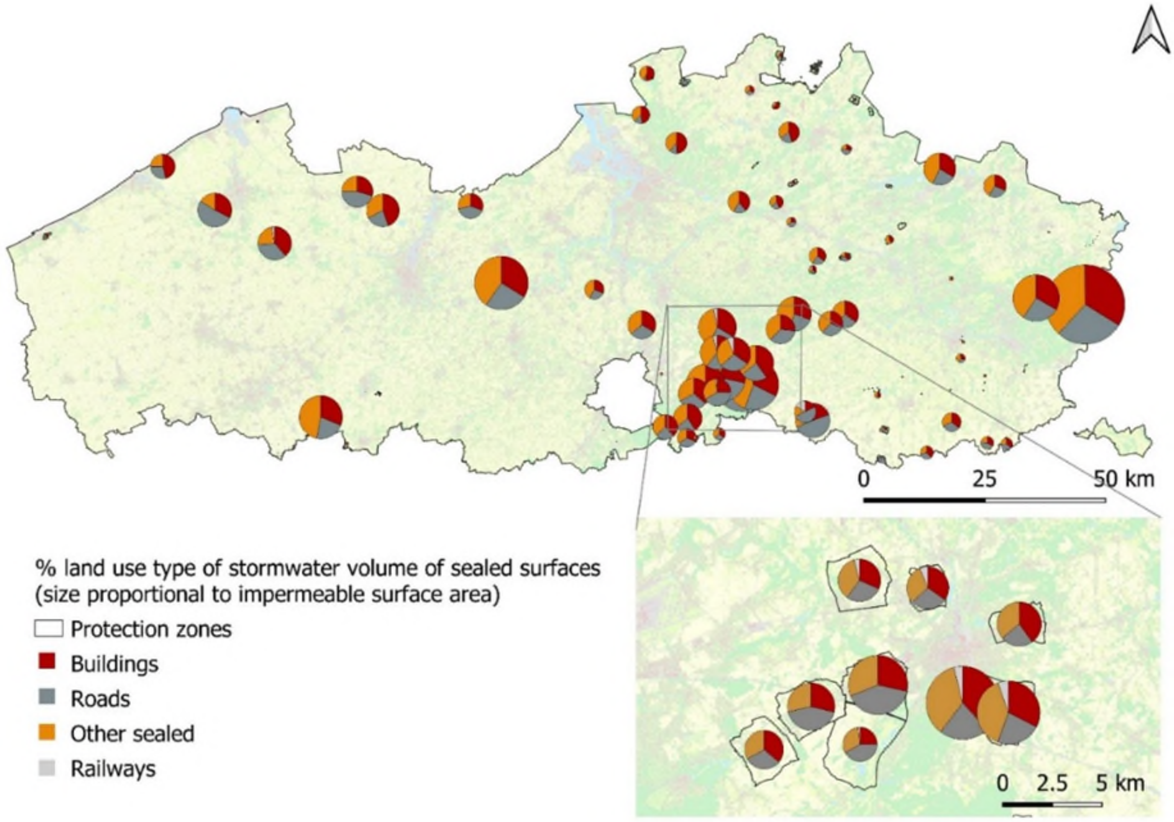

Figure 2: Subcategories distribution of urban, impervious land cover type, based on data from Agentschap Digitaal Vlaanderen (2018) (sizes relative to impermeable surface area)

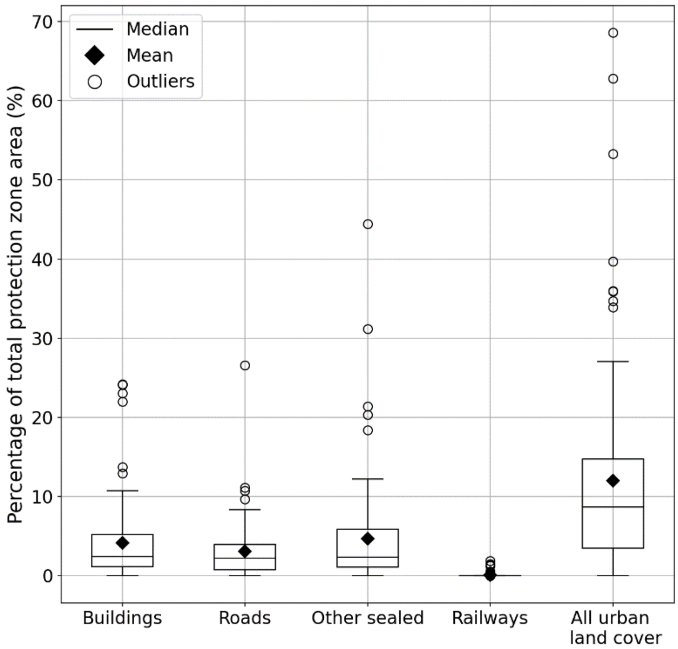

Figure 3: Boxplots of fractions of urban land cover types within protection zones

Based on this land cover map, potential stormwater volumes from impermeable surfaces in protection zones were calculated (Figure 4). Calculated stormwater volumes range between 0 to 2.768.436 m³ per year, with the largest stormwater volumes indicated in

*Table 3*2. These calculated stormwater volumes depend on (1) the fraction of impermeable land cover type in the area, related to the level of urbanization, and (2) the size of the protection zone. This illustrates the logical consequence that larger protection zones can have bigger impacts on stormwater infiltration as larger stormwater volumes can be generated. The highest potential stormwater volume is therefore also noticeable in the large protection zone of Maasmechelen. Other protection zones located south of the city of Leuven and the smaller urban areas of Berlare and Zele show high stormwater availability because of the size and urbanization levels of these zones.

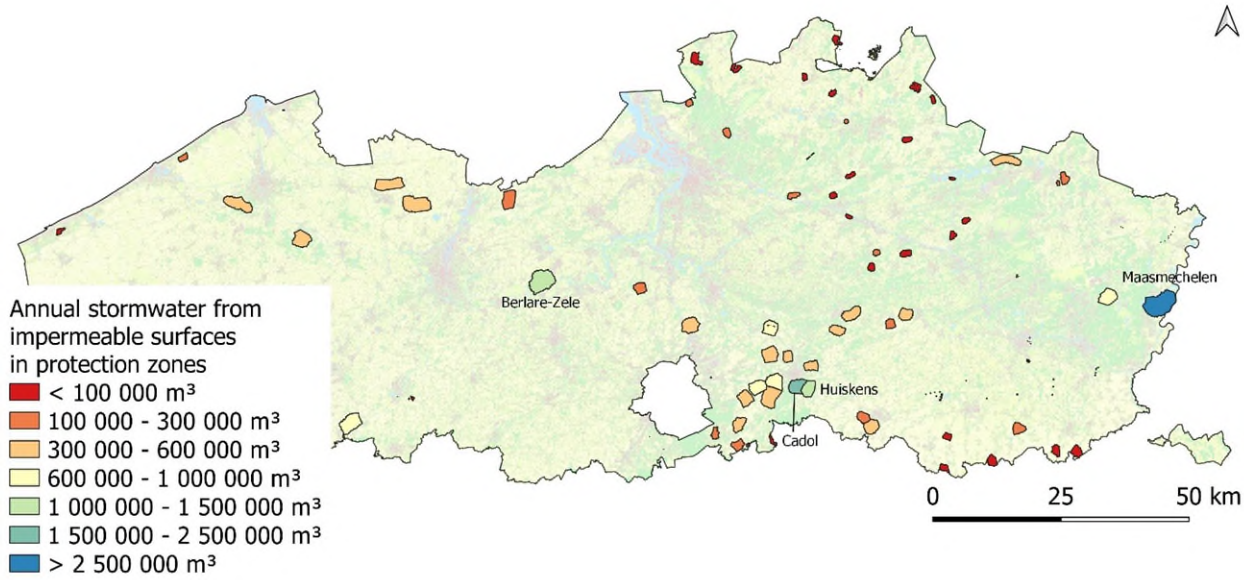

Figure 4: Annual maximum stormwater volumes from impermeable surfaces available for infiltration

Table 2: Calculated stormwater volumes for protection zones with stormwater volumes > 500 000 m³ / year. A complete list of stormwater volumes for all Flemish protection zones can be found in Appendix I.

Protection zone name	Protection zone size (m²)	Potential stormwater volume (m³/year)
Eisden-Vrietselbeek-Meeswijk	22 140 117.0	2 768 436.0
Abdij-Cadol	7 090 239.0	1 500 719.0
Berlare-Zele	16 726 334.0	1 266 812.0
Huiskens	6 659 715.0	1 124 685.0
Egenhoven	7 798 020.0	991 185.0
As	8 289 871.0	954 897.5
Avelgem-Waarmaarde-Kerkhove	11 206 677.0	821 268.3
Den Dijk	6 740 738.0	637 578.3
Leefdaal	7 249 301.0	633 974.6
Vlierbeek	4 499 975.0	552 986.8
Groot-Overlaar	6 541 269.0	530 359.4
Schoonhoven-Weerderlaak	6 982 900.0	522 163.4
Winksele"Kastanjebos"	7 742 820.0	509 235.8
Snellegem	10 745 655.0	507 632.8

Several drinking water companies operate in different regions of Flanders, of which De Watergroep and Pidpa consist of the majority of groundwater wells of protection zones. A comparison between stormwater volumes of the protection zones of both drinking water companies clearly shows a higher stormwater availability for protection zones of De Watergroep with a t-statistic of 2.82 and a p-value of 0.006 (Figure 5). This can be explained by the larger protection zone sizes and higher percentage of impermeable surfaces in the protection zones of De Watergroep (Appendix IV).

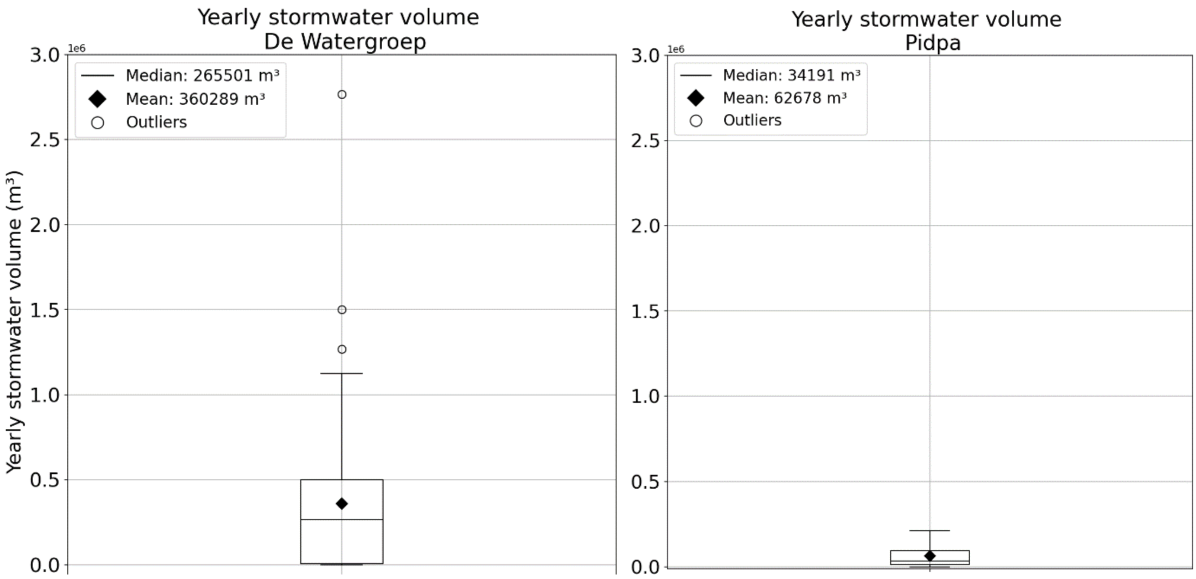

Figure 5: Comparison of yearly stormwater volumes (in million m^3) in protection zones of De Watergroep (left) and Pidpa (right)

2.3.2 Potential impact of stormwater infiltration on groundwater recharge

Next, an assessment is made on how far these stormwater volumes could potentially contribute to extra groundwater recharge in Flemish protection zones. Calculated stormwater volumes are therefore compared to (1) estimates of current groundwater recharge and (2) maximum pumping volumes from phreatic aquifers.

2.3.2.1. Comparison with current groundwater recharge

The first comparison shows a high potential for extra groundwater recharge in Flemish protection zones (Figure 6) with a wide spatial variability in potentials for different protection zones (Figure 9, left and

Table *3*). Protection zones with a percentage higher than 100% have the potential to double groundwater recharge if all stormwater would recharge the aquifer. The highest potentials are noticeable in protection zones around the urban area of Leuven (e.g., Huiskens, Herent, Cadol). However, also protection zones with percentages lower than 100% have a high potential, as Figure 9 (left) shows that the average and median fraction of extra stormwater volume compared to current groundwater recharge are respectively 38 % and 20 %. The calculated percentage for all protection zones combined amounts to 29 %, which indicates that groundwater recharge could be enhanced by approximately 1/4th through stormwater infiltration and aquifer recharge practices in protection zones in Flanders.

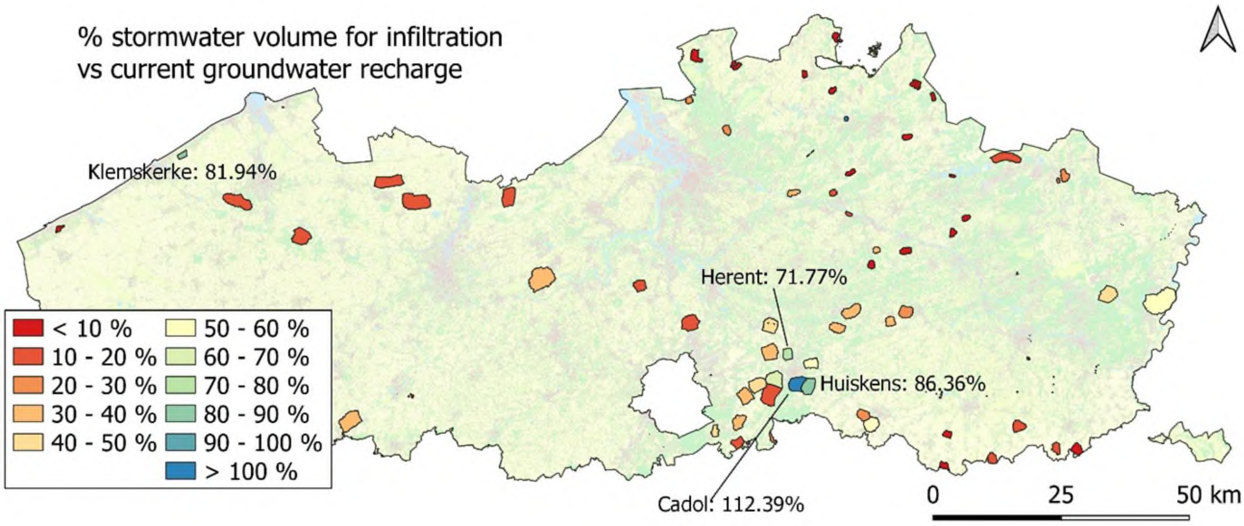

Figure 6: Comparison of stormwater volumes versus current groundwater recharge

Table 3: Protection zones with percentages of stormwater versus current groundwater recharge > 40%. A complete list of stormwater volume percentages versus current groundwater recharge for all Flemish protection zones can be found in Appendix 2. Bigger protection zones (> 1 000 000 m² or 100 ha) indicated in bold.

Protection zone name	Protection zone size (m²)	Comparison potential stormwater volumes versus current groundwater recharge (%)
Vilvoorde	1 281	412
Kooigem-WPC Spiere-Helkijn	261	295
Knokke-Heist	17 632	155
Nieuwerkerken	6 508	146
Beerse	569 519	126
Abdij-Cadol	**7 090 239**	**112**
Hasselt	16 256	102
Huiskens	**6 659 715**	**86**
Opitterkiezel	5 191	84
Bredene	**1 856 224**	**81**
Trekschuren	225 980	81
Bijlokestraat	**3 628 456**	**71**
Egenhoven	**7 798 020**	**68**
Eisden-Vrietselbeek-Meeswijk	**22 140 117**	**56**
Spiere	29 292	56
Vlierbeek	**4 499 975**	**55**
Groot-Overlaar	**6 541 269**	**50**
Hoeilaart	**2 500 386**	**48**
Vliermaal	52 962	45
Heusden-Zolder	56 320	44
Leefdaal	**7 249 301**	**44**
Den Dijk	**6 740 738**	**44**
As	**8 289 871**	**41**
Zaventem	36 408	40

A comparison between the two drinking water companies De Watergroep and Pidpa (Figure 7) shows an almost significant difference in stormwater recharge potential versus current groundwater recharge, with a t-statistic of 1.97 with a p-value of 0.053, with a higher potential of stormwater recharge for protection zones of De Watergroep. This can be explained by the higher percentage of imperviousness in protection zones of De Watergroep compared to Pidpa (Appendix IV), as Pidpa is mostly active in the province of Antwerp, in the region of the Kempen which has a lower population density compared to the average population density of Flanders (Streekplatform Kempen, 2018; Vlaamse Milieumaatschappij, 2019).

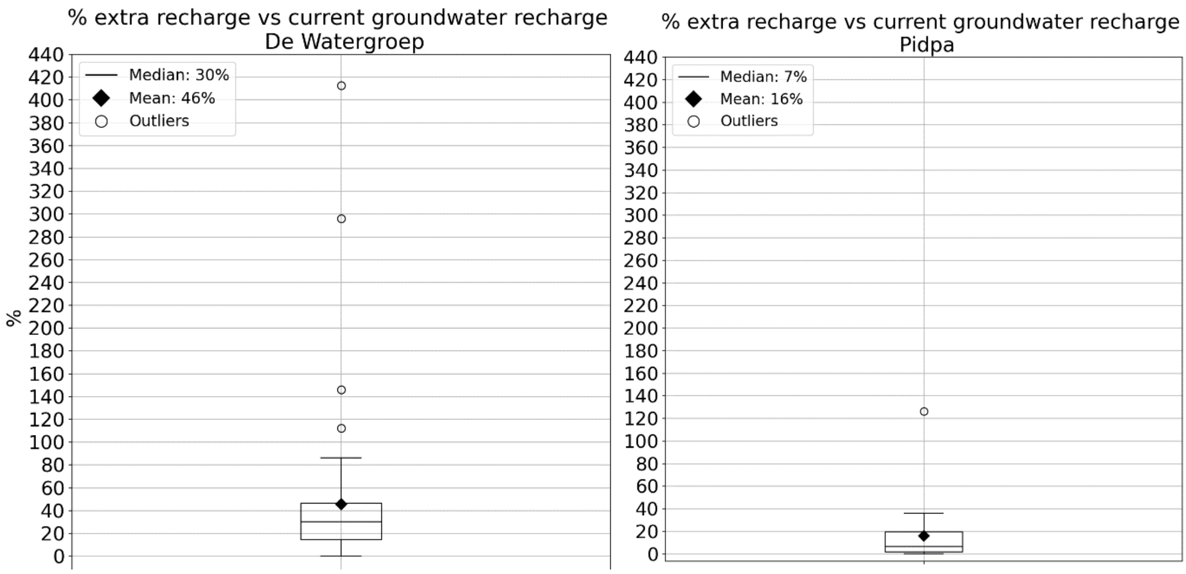

Figure 7: Comparison of stormwater potential versus current groundwater recharge for De Watergroep (left) and Pidpa (right)

2.3.2.2. Comparison with abstracted pumping volumes for drinking water production

A comparison with groundwater abstraction rates for drinking water production (Figure 8 and Table 4) shows a similar spatial pattern. Protection zones with percentages higher than 100% are noticeable around Leuven (e.g., Herent, Kessel-lo, Egenhoven, Huiskens), indicating high stormwater infiltration potential. This illustrates that drinking water abstraction volumes can be compensated by these stormwater volumes. Also, other protection zones show significant percentages, with an average of 47.88% (Figure 9, right). Taking into account protection zone sizes, the stormwater availability amounts to 1/3rd of the available phreatic pumping rates.

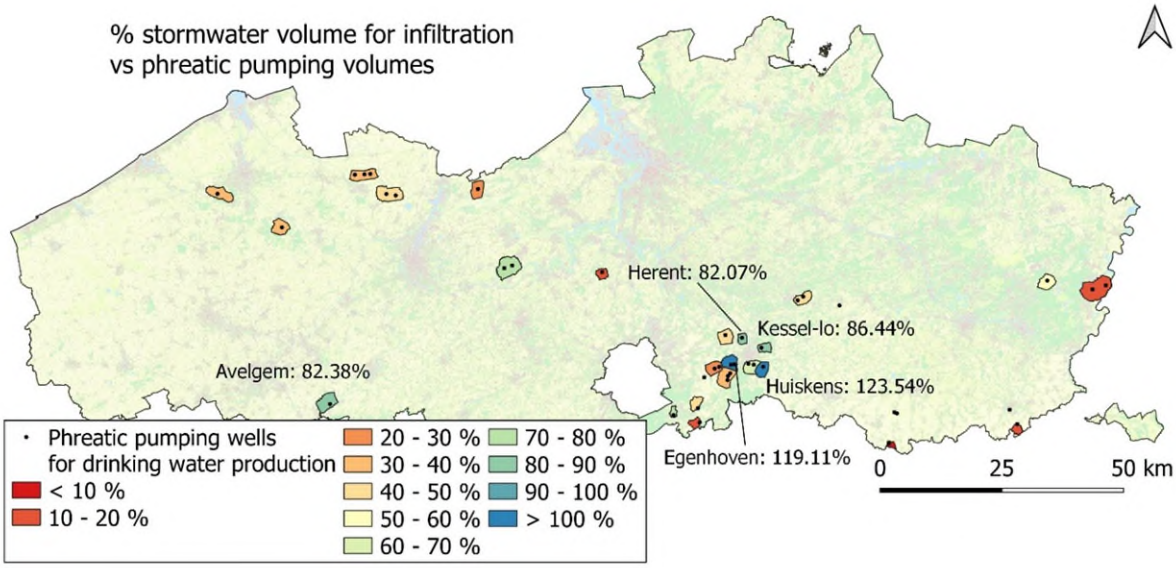

Figure 8: Comparison of stormwater volumes versus yearly pumping volumes for drinking water production from phreatic aquifers

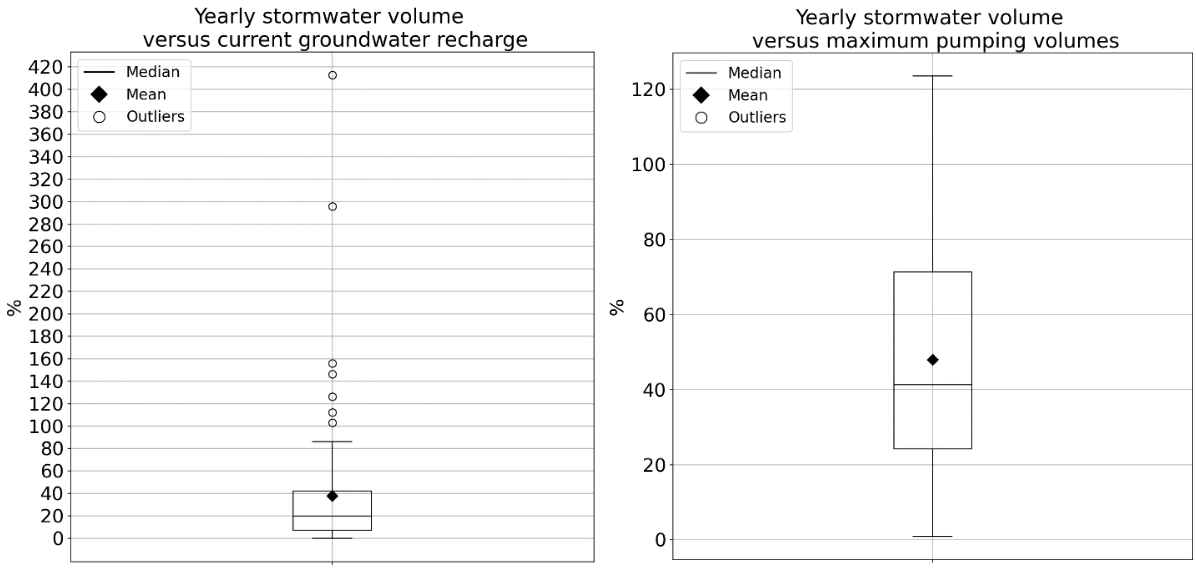

Figure 9: Boxplots of comparison of stormwater volumes with modelled natural groundwater recharge (left) and with measured maximum yearly pumping volumes of the period 2016-2020 (right)

Table 4: protection zones with percentages of stormwater volumes versus pumping volumes from phreatic aquifers > 40%. A complete list of stormwater volumes for all Flemish protection zones can be found in Appendix III.

Protection zone name	Protection zone size (m²)	Comparison yearly potential stormwater volumes versus pumping volumes (%)
Huiskens	6 659 715	123
Egenhoven	7 798 020	119
Vlierbeek	4 499 975	86
Avelgem-Waarmaarde-Kerkhove	11 206 677	82
Bijlokestraat	3 628 456	82
Hoeilaart	2 500 386	76
Berlare-Zele	16 726 334	71
Abdij-Cadol	7 090 239	63
As	8 289 871	53
Winksele"Kastanjebos"	7 742 820	48
Schoonhoven-Weerderlaak	6 982 900	48
Kouterstraat-Nellebeek	5 344 274	47
Lembeke-Oosteeklo	14.122 212	41

2.3.2.3. Analysis for infiltration zones of pumping wells De Watergroep

The protection zones around drinking water wells have been established in 1985-1995. More recent modelling exercises have shown that the infiltration zones of drinking water wells do not completely overlap with the zones delineated and anchored in legislation. Therefore, the same GIS analysis has also been carried out for the infiltration zones of the drinking water company De Watergroep. The comparison to the current groundwater recharge in infiltration zones (Figure 10) shows similar spatial patterns of stormwater infiltration potential compared to the analysis for the protection zones. Highest potentials are again noticeable in the zones around Leuven. The comparison with phreatic pumping volumes in infiltration zones of De Watergroep shows similar, but often higher potentials for the analysis with the infiltration zones (Figure 11). This can be related to the fact that these infiltration zones are often bigger than the delineated protection zones. Therefore, more stormwater volumes can be generated, whereas the pumping volumes remain constant.

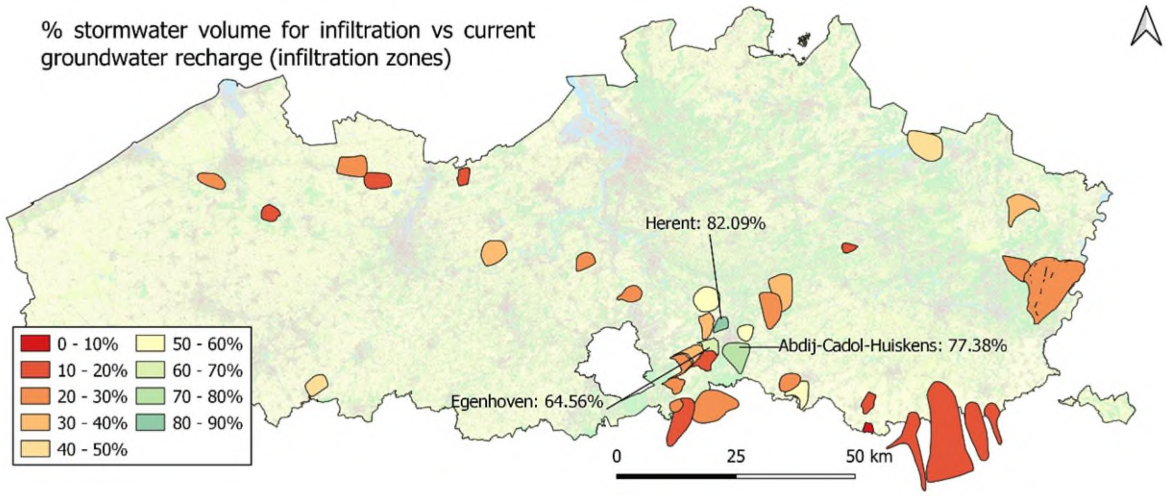

Figure 10: Comparison of stormwater volumes versus current groundwater recharge for infiltration zones of De Watergroep

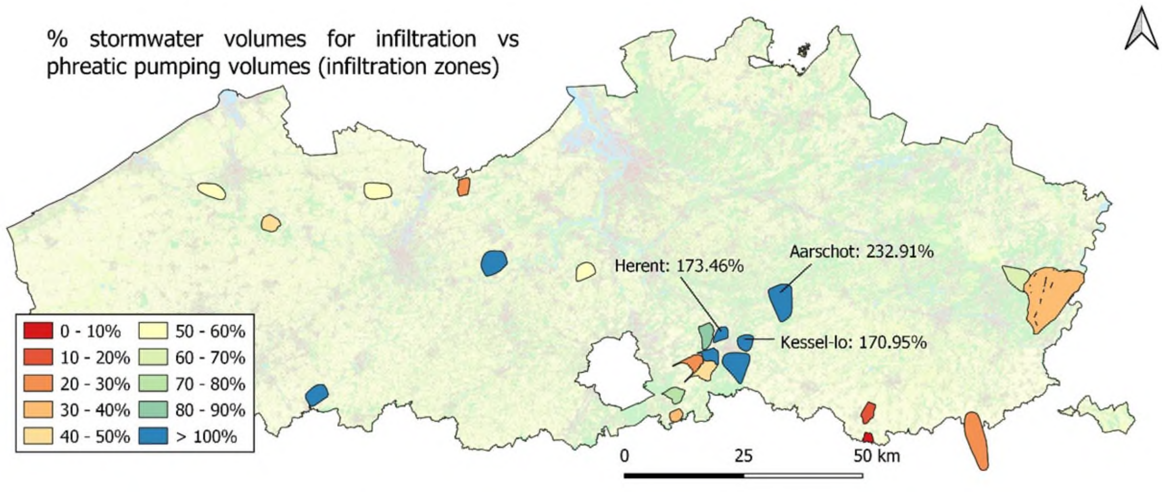

Figure 11: Comparison of stormwater volumes versus phreatic pumping volumes for infiltration zones of De Watergroep

2.4 Preliminary conclusion on GIS analysis on stormwater infiltration and recharge potential

The comparisons of stormwater volumes with (1) current recharge and (2) phreatic pumping volumes show a high potential for groundwater recharge enhancement due to stormwater infiltration. Zomlot et al. (2017) calculated changes in Flemish groundwater recharge between 2006-2013, predominantly due to the conversion of agricultural to impermeable, urban areas, resulting in decreases of groundwater recharge up to 35% locally. Enhancement of stormwater infiltration can therefore significantly contribute to counteracting this phenomenon. This practice can also contribute to compensating climate change impacts on groundwater recharge. Climate change predictions indicate differing impacts on groundwater recharge worldwide, with generally a reduction in recharge for Belgium, but with remaining high uncertainties (Atawneh et al., 2021; Reinecke et al., 2021). Sumaqua (2022) estimates a median of 20% decrease in groundwater recharge by 2100 for Flanders with spatial variations, which could therefore be compensated by the predicted 29% increase in groundwater recharge from stormwater infiltration.

3 Desktop review of the impact on groundwater quality

3.1 Inventory of related projects

A desktop research and meetings with organizations with similar projects have been carried out in order to obtain an overview of related projects and to look for potential cooperation and to avoid duplicating work. Table 5 shows a non-exhaustive overview of related projects in Belgium and Europe.

Table 5: Non-exhaustive overview of similar projects in Belgium and Europe

Project name	Belgian or Dutch partners?	Study area	Topic and reports	Links
LIFE Belini	VMM, Leefmilieu Brussel	Flanders and Brussels (Belgium)	Runoff water quality measurements campaign in Brussels (Leefmilieu Brussel, 2022) Sanering wegwater (Witteveen+Bos & VMM, 2019)	https://www.life-belini.be/nl/
StopUP – case 4	Belgian partner: Aquafin	Flanders (Belgium)	Treatment of high traffic roads and residential areas in Antwerp region	https://stopup.eu/
PROWATER	Belgian partners: Flanders, Natuurpunt, Provincie Antwerpen, Pidpa, Universiteit Antwerpen	Demo sites in Belgium, Netherlands, UK	Build resilience against droughts (and water scarcity) by enhancing infiltration and water retention capacity of landscapes in regions of strategic importance for drinking water production	https://www.pro-water.eu/
BoNuS	KWR	Netherlands	Bodempassage Nieuwe Stijl (BoNuS) – Verkenning van actievere mogelijkheden voor de inzet van bodempassage ter verlaging van de waterzuiveringsinspanning voor organische microverontreinigingen (KWR, 2018)	https://edepot.wur.nl/509349
STOWA database	stowa	Netherlands	Kwaliteit afstromend hemelwater in Nederland - Database kwaliteit afstromend hemelwater in Nederland (stowa, 2020)	https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202020/2020-05%20STOWA%202020-05%20Kwaliteit%20van%20afstromend%20hemelwater%20in%20Nederland.pdf
UPWater	/	Case study sites in Denmark, Greece, Spain	Understanding groundwater pollution to protection and enhance water quality	https://www.upwater.eu/
Life DrainRain	/	Spain	Runoff water purification from pavements: a novel integral system of pervious concrete pavement & insitu water treatment	http://www.lifedrainrain.com/en/home/

D4RUNOFF	/	Case study sites in Denmark, Spain, Italy	Preventing and managing pollution from urban water runoff	https://d4runoff.eu/

3.2 Literature review of water quality of urban runoff

3.2.1 Water quality of urban runoff

Stormwater runoff from urban landscapes has long been a cause for environmental concern due to its chemical complexity, toxicity to aquatic organisms, and temporal and spatial dynamics. Nutrients, heavy metals, bacteria, chlorophenols, and polycyclic aromatic hydrocarbons (PAHs) are commonly reported in stormwater runoff. Limited research has shown that stormwater also can contain emerging contaminants such as pesticides, pharmaceuticals, personal care products, industrial pollutants such as per- and polyfluoroalkyl substances alkyphenol surfactants, phthalates and flame retardants and tire wear particles. The presence of these substances in stormwater are of great concern due to their persistence and mobility in combination with their toxic, genotoxic, mutagenic and carcinogenic properties.

A recent study on water quality of urban stormwater is the work of Masoner et al. (2019). This paper presents results from 50 runoff events at 21 sites across the United States. In this national scale study 438 organic and 62 inorganic chemicals were measured in urban stormwater. It was demonstrated that stormwater transports substantial mixtures of polycyclic aromatic hydrocarbons, pesticides, pharmaceuticals, and other organic chemicals known or suspected to pose environmental health concern. Of the 438 organic chemicals analyzed, 215 (49%) were detected in one or more stormwater samples with 223 (51%) not detected in any sample. Stormwater can thus contain high numbers of organic micropollutants. The number of organic chemicals detected in a single stormwater sample ranged from 18 to 103 (median = 73; Figure 12A). Pesticides were the most frequently detected chemical group (accounting for 35% of total detections; Figure 12A). Cumulative organic-chemical concentrations of samples ranged from 4370 ng/L to 263 000 ng/L (median = 48 500 ng/L); with 7 samples having a total concentration exceeding 100 000 ng/L (100 µg/l) (Figure 12B).

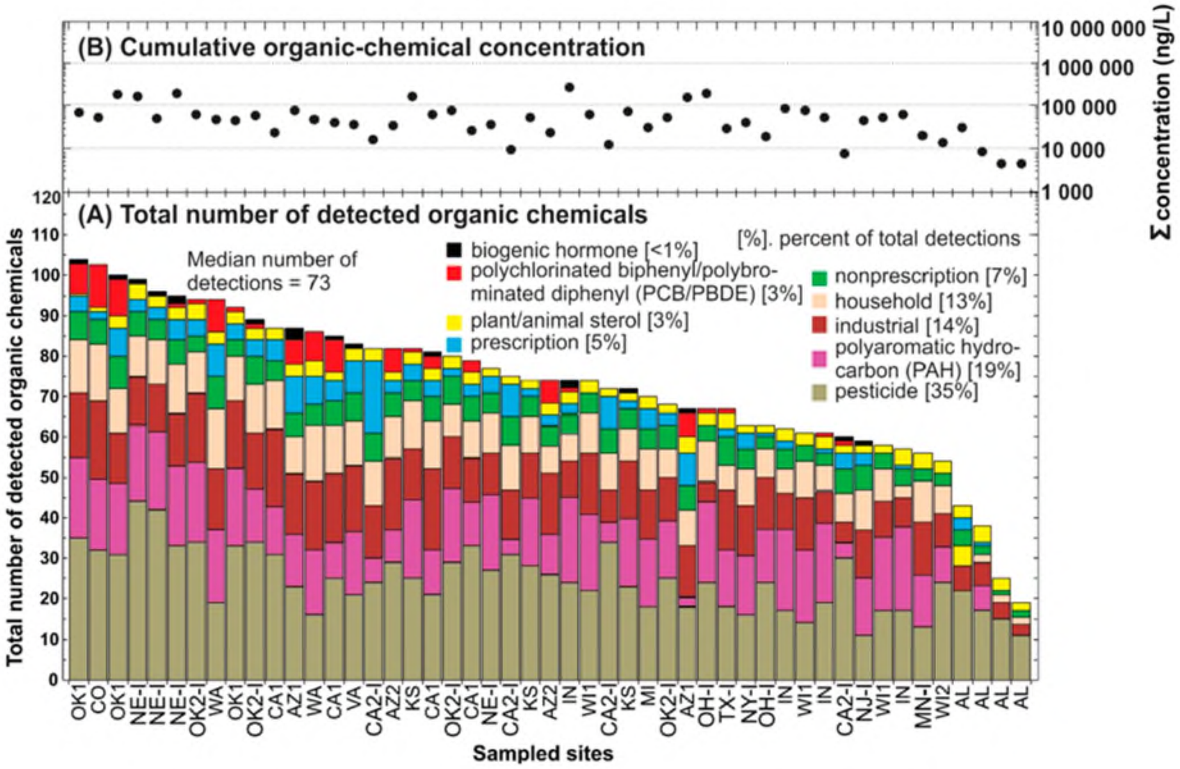

Figure 12: Total number of detected organic chemicals for sampled sites, sorted from left to right by decreasing number of detections (A) and total measured organic-chemical concentration for sampled sites (B) (Masoner et al., 2019)

Another comprehensive survey of micropollutants was carried out by Wicke et al. (2021) for different land-use types in Berlin. Event mean concentrations were measured for a set of 106 parameters including 85 organic micropollutants in 5 different catchments. 77 of the 106 substances were found at least once during the measurement campaign. On average the measured stormwater contained a mix of 24 µg/l organic micropollutants with the plasticizer diisodecyl phthalate in the highest concentrations in all catchments (Figure 13). Each catchment type had specific dominant organic micropollutants. For instance, flame retardants in commercial areas, new high-rise buildings and old building areas, pesticides in a catchment dominated with one family homes and PAHs, heavy metals Ti, V, Cr and Ni, benzothiazoles and benzotriazoles in a catchment dominated by heavy traffic. If only the sum parameter of PAH is considered, old building areas, traffic dominated catchments and commercial areas show the highest mean concentrations for respectively 31%, 31% and 19% of the substances found in the study of Wicke et al. (2021). Above is in line with the findings of Muller (2022) who concludes that traffic activities and building surface materials are major sources of micropollutants in stormwater.

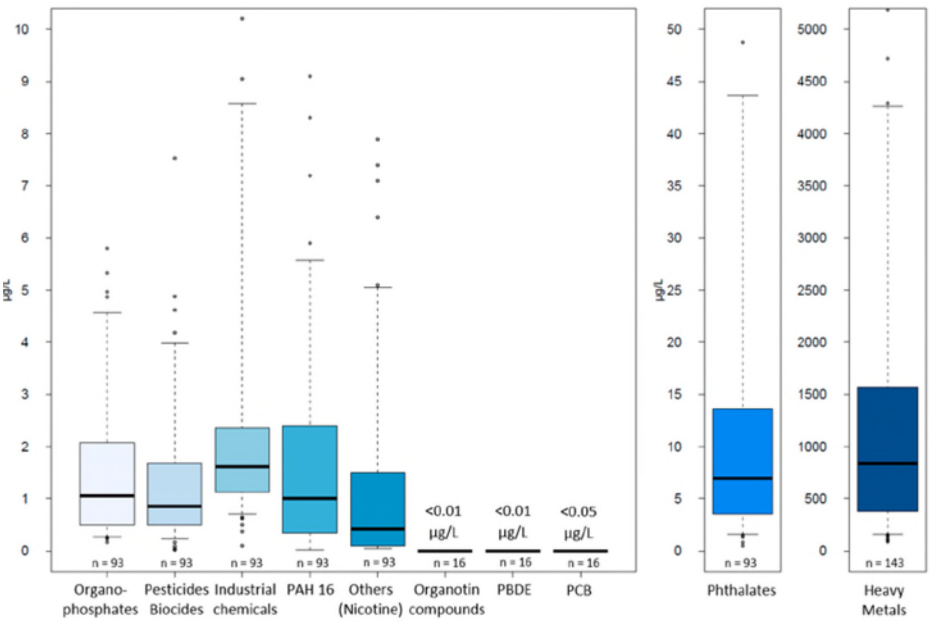

Figure 13: Concentration boxplots of micropollutant groups (sum of substance concentration per group) in stormwater from all the catchments sampled. 25%/75% quantiles shown as boxes, median as thick line and whiskers show 5%/95% quantiles (Wicke et al., 2021)

3.2.1.1. Belgium

Witteveen+Bos & VMM (2019) conclude in their literature review on Flemish road stormwater quality that main road contaminants include heavy metals, PAHs, oils and chlorides. However, a big proportion is sorbed to suspended solids, which means that a settling tank with removal of the sludge formation is essential for treatment of the road water. Additionally, infiltration of stormwater next to the road leads to contamination up to 10 meters from the road, and it is recommended to remove the topsoil every 8-10 years (Witteveen+Bos & VMM, 2019). Higher concentrations of suspended solids, chlorides, heavy metals and PAHs have been observed in stormwaters from highways in Flanders (Witteveen+Bos & VMM, 2019). Additionally, Leefmilieu Brussel (2022) found a large variability of concentrations in road and roof runoff samples in Brussels. Next to the higher concentrations of classical road pollutants such as PAHs, heavy metals and oils, also pesticides including glyphosate, AMPA and diuron were found, despite the urban context of Brussels (Leefmilieu Brussel, 2022). Diuron is primarily used for algal/plant control on building materials, Glyposate and its decay product AMPA are widely used for weed control (Wicke et al., 2021). Furthermore, road traffic can lead to microplastic pollution from rubber car tires. VMM et al. (2021) estimate that yearly 245 926 kg rubber particles from tire wear end up in the Flemish environment, which is higher than the yearly amount of microplastics from residential wastewaters. However, the risk from microplastics for surface waters, soil organisms and tap waters are assessed to be small to negligible (VMM et al., 2021).

3.2.1.2. Netherlands

The first comprehensive study on stormwater runoff quality in the Netherlands already dates back to 1982. Since then, many investigations have been performed by municipalities and water boards under different field settings. In 2007 a first attempt was made to bring the measurements from these studies together in one accessible database (Boogaard & Lemmen, 2007 a,b). In 2019 the database was updated resulting in 1742 samples from 191 locations in the Netherlands (Liefting et al, 2020). The analysis in the database is predominantly focused on nutrients, heavy metals, mineral oil, PAHs, some pesticides and fecal indicator organisms (Table 6). The database, however, contains (very) limited data on other substances such as emerging contaminants.

Table 6: Median, d10 and d90 of 16 commonly analyzed substances in the STOWA database on runoff quality (Liefting et al., 2020)

Substance	Unit	Median	d10	d90
Cadmium (Cd)	µg/l	0.09	0.01	0.58
Copper (Cu)	µg/l	11	3.3	41
Mercury (Hg)	µg/l	0.02	<0.02	0.07
Lead (Pb)	µg/l	8	1.8	86
Nickel (Ni)	µg/l	1.9	0.5	8.0
Zinc (Zn)	µg/l	70	11	290
Anthracene	µg/l	0.002	0.001	0.0077
Benzo(a)-pyrene	µg/l	0.004	0.002	0.031
Mineral oil	µg/l	60	<50	470
COD	mg/l	25	12	76
P-total	mg P/l	0.21	0.06	0.52
N-Kjeldahl	mg N/l	1.5	0.68	4.0
Ammonium NH_4-N	mg N/l	0.48	<0.05	2.16
Nitrate NO_3-N	mg N/l	0.72	0.32	2.2
TSS	mg/	14	4.2	70
E coli	cfu/100 ml	$6.2\ 10^2$	$2.1\ 10^1$	$2.1\ 10^4$

Liefting et al. (2020) made a comparison between the data before 2007 and the data between 2007 and 2019 for a selection of substances in combined effluent from roofs and roads in residential areas. The quality seemed to have improved with statistically significant reductions in average concentration for lead (from 30 to 16 µg/l), zinc (from 183 to 125 µg/l), benzo(a)pyrene (from 0.081 to 0.018 µg/l), CZV (from 51 to 32 mg/l) and Kjeldahl nitrogen (from 2.6 to 2.0 mg/l). Based on the data availability it was not possible to find statistically sound analysis on subcategories such as roofs or road runoff only or for other categories such as industrial areas. Measurements in industrial areas show strong variation between sites, and as a result, not usable for generic conclusions.

The bulk of the data in the STOWA database concerns total concentrations in non-filtrated samples. It is however, well known that a large fraction of substances in runoff is bound to suspended solids and especially to the finer fractions. Boogaard et al. (2014) analysed the fractionation for 90 samples from 25 locations in the database with both total and dissolved concentrations (Figure 14) resulting in bound fractions of well over 50% for metals and PAHs.

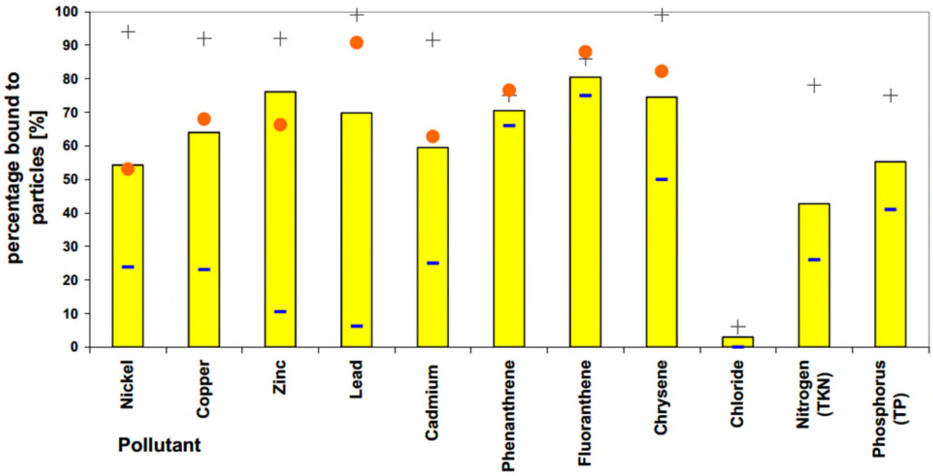

Figure 14: Average percentage bound to particles in the STOWA database (yellow bars with min and max value denoted with – and +) and average values from international literature (orange dots) (Boogaard et al., 2014)

Compared to international databases (such as the National Stormwater Quality Database USA), Dutch stormwater runoff seems to be relatively clean. According to Liefting et al. (2020) this might be due to the low concentration of suspended solids in the sampled runoff. As mentioned above, a low concentration of suspended solids will lead to lower concentrations because a large part of analysed substances are particle bound. The typical layout of Dutch storm drains (small slope, often permanently waterfilled) results in low flow velocities and settlement of particles, which in return result in relatively low concentrations at the outlets where sampling takes place.

As mentioned before, water quality analysis in most studies is limited to macroparameters, oil, PAHs and heavy metals. Studies including other organic micropollutants are very scarce. One of the first studies including other organic micropollutants was carried out on stormwater from the N224 road near La Cabine drinking water pumping station in Arnhem (Beekman et al., 1998). This analysis included 4-tert. butylphenol, tri(2-chloroethyl)phosphate, 2-methylthiobenzothiazool, isoindool-I,3-dion and dimethylphthalate. Samples were taken from runoff and from the soil below the infiltration ponds. It was concluded that some of the micropollutants were able to reach the groundwater table at 9 m below the surface. Due to the limited amount of infiltrating runoff and dilution with unpolluted groundwater the risk for the drinking water production was deemed low.

To get more grip on the occurrence of organic micropollutants in stormwater Langeveld et al. (2020) developed a fingerprinting method inspired by Launay et al. (2016). This method uses the extensively measured water quality of combined communal sewage influent. Substances and concentrations found in this influent are unmixed using tracers (e.g., diclofenac) which are only found in the dry weather flow. Using this technique Langeveld et al. (2020) were able to identify substances and concentrations in stormwater feeding the sewage treatment plants. Organic pollutants (beside PAHs) identified in stormwater above two times the detection limit are the herbicide glyphosate, several organic pesticides, fungicides, flame retardants and a plasticizer/solvent. See

Table 7 for an overview. Seven stormwater related substances in this table are considered a problematic substance for drinking water production according VEWIN. Fipronil and permethrin are dominantly found in dry weather flow but are also estimated in the stormwater flow. The latter is however uncertain due to the possibility of leaching from in-sewer stocks originating from dry weather flow. The large number of pesticides is in line with the findings of Masoner et al. (2019) in the USA, the Leefmilieu Brussel (2022) study and recent field studies. Glyphosate and its decay product AMPA for instance were found in stormwater in Rheden and Rotterdam (Zuurbier & Van Dooren, 2019) and Almere (Langeveld et al., 2016). Other pesticides or related substances found (in low concentrations) in in the Rotterdam study were antrachinon, DEET, flufenacet (an upcoming herbicide in potato farming) and dithiocarbamates. Agriculture-related herbicides such as flufenacet can thus be found in stormwater miles from its location of use.

Table 7: Calculated concentrations in stormwater based on fingerprinting combined sewage treatment plant influent in the Netherlands (from Langeveld et al., 2020)

Substance	Average calculated concentration in stormwater (µg/l)	Remark
Glyphosate	4.6	herbicide, VEWIN problematic substance
N,N-diethyl-3-methylbenzamide	1.5	insect repellent, VEWIN problematic substance
fipronil	0.0066	insecticide (near detection level)
phthalimide	0.5	used in fungicides
N,N-diethyl-3-methylbenzamide (DEET)	5.3	insect repellent, VEWIN problematic substance
permethrin	0.013	insecticide (near detection limit)
terbuthylazine	0.53	herbicide, VEWIN problematic substance
dimethenamid-P	0.09	herbicide, VEWIN problematic substance
chloorprofam	0.04	germ inhibitor
S-metolachlor	0.048	herbicide, VEWIN problematic substance
diuron	0.11	Herbicide (banned), biocide in building materials
desethylterbutylazine	0.19	herbicide
prosulfocarb	0.14	herbicide
tebuconazol	0.26	fungicide, wood preservation
2-methyl-4-chloorfenoxyazijnzuur	0.54	fungicide
mecoprop-P	0.91	herbicide, biocide in building materials VEWIN problematic substance (only found at two treatment plants)
simazine	0.07	herbicide, prohibited in the EU
pentachlorobenzene	0.007	flame retardant and fungicide
trichloropropylphosphate (TCPP)	4.25	flame retardant
triisobutylphosphate	0.46	plasticizer/solvent

3.2.2 Sources of pollution

Major sources of contaminants in urban stormwater that have been distinguished in literature are vehicular traffic, atmospheric deposition, and leaching from building envelopes. This indicates that the source of contamination differs per surface type. Here, we can distinguish roofs and buildings, roads and parking plots and open spaces like public parks, shopping areas etc.. In the next paragraphs we explore the occurrence of contaminants per surface type in more detail.

3.2.2.1. Roof runoff

As roofs represents a major part of the urban impervious surface, roof runoff is considered an important source of urban stormwater contamination. The runoff water can be contaminated by a wide range of (micro)pollutants, and in concentrations often exceeding surface water quality and/or drinking water standards (De Buyck et al., 2021). In a review study, De Buyck et al. (2021) collected and summarized information from almost 180 publications about contaminants in stormwater, roof runoff and atmospheric deposition. Almost 350 were detected, including heavy metals, PAHs, pesticides, phthalates, organophosphorus flame retardants, nitrophenols, alkylphenols (Aps), alkylphenol ethoxylate (APEOs), polybrominated diphenyl ether (PBDEs) and polychlorinated biphenyl (PCBs) in roof runoff and/or atmospheric deposition. Figure 15 and Figure 16 show the results from the study of De Buyck et al. (2021) for pesticides and a group of other pollutants. A critical aspect about this review study is that it contains information from older studies, even before the year 2000 and therefore the findings might be somewhat outdated in terms of chemicals that have been banned over the years. Treated wood roofing and metallic rooftops (copper and zinc) were found to have the highest impact on water quality. Paints and plasters of facades and roof sealing membranes can be a source of biocides in urban areas.

In general, atmospheric deposition and corrosion of roofing materials are the main pollution sources of roof runoff (De Buyck et al., 2021; Gwenzi et al., 2015; Song et al., 2019), and the roofing material is an important determining factor (De Buyck et al., 2021; Deng, 2021; Gwenzi et al., 2015). For example, stormwater from metal roofs can contain lower concentrations of bacteria (Mendez et al., 2011), but higher trace metal concentrations (De Buyck et al., 2021). In addition, Burkhardt et al. (2007) reports the presence of biocides in urban stormwater which main sources seem to be building envelopes, i.e. facades (paints, plasters) and roof sealing membranes. Concentrations of tertbutyl, carbendazim, diuron, mecoprop and Irgarol® 1051 were found in stormwater runoff in concentrations exceeding 0.1 µg/L even after a first flush. The use of Diuron is banned as herbicide in the Netherlands and Flanders and declared a priority substance in the EU but might still be present as a biocide in building materials such as paints, treated wood and bitumen (Vlaamse Milieumaatschappij, 2017; ECHA substance infocard). Wicke et al. (2021) point out that the occurrence of Diuron and mecoprop might depend on regional use patterns of French and German roof/paint suppliers. Mecoprop for instance was the most prominent biocide found in the Berlin study of Wicke et al. (2021), whilst in France diuron was the most prominent biocide found (Gasperi et al., 2014). Both diuron and mecoprop were found to be present in relatively high concentrations in Dutch stormwater with calculated mean concentrations of respectively 0.11 and 0.91 µg/l (

Table 7) using the fingerprinting method on WWTP influent (Langeveld et al., 2020) discussed earlier. Mecoprop, however, was found at only two WWTP's. Organophosphates such as TCPP and TBEP are in growing use as flame retardants in insulation materials in the EU due to the ban of pentabroomdifenylether. Wicke et al., 2021 found the highest concentrations of these substances in a commercial area followed by catchments with old and new buildings. TCPP was calculated in high concentrations (mean concentration 4.2 µg/l) in Dutch stormwater based on the fingerprinting method (Table 7).

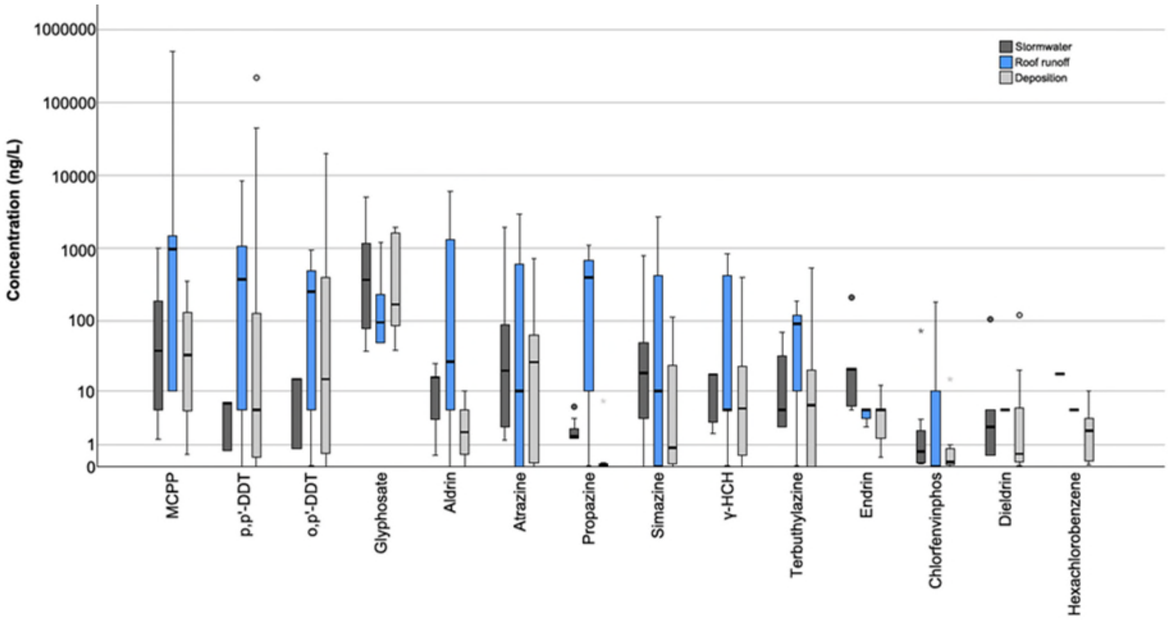

Figure 15: Overview and comparison of pesticides in stormwater, roof runoff and deposition (De Buyck et al., 2021)

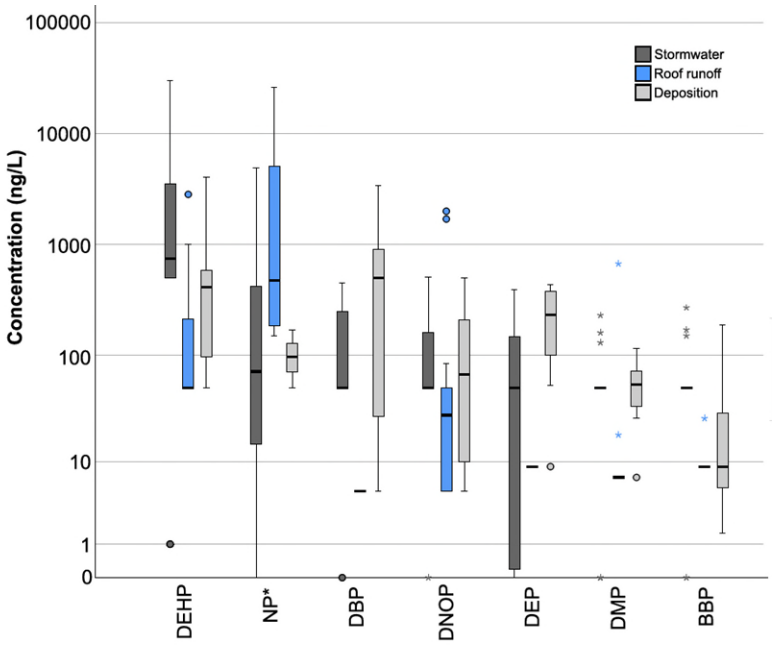

Figure 16 Overview and comparison of other organic pollutants including phthalates and NP in stormwater, roof runoff and deposition (De Buyck et al., 2021)

3.2.2.2. Vehicle related surfaces: roads and parking lots runoff

Vehicular traffic was among the first sources identified as contributing significantly to the pollution of stormwater runoff (Muller, 2022) and has therefore been studied extensively in this context. The study of Muller (2022) provides a comprehensive review on contamination of vehicle related surfaces. Early studies often evaluated road and highway runoff quality primarily on the basis of total suspended solids (TSS), nutrients, and metals. Two major pollution sources associated with vehicular traffic and roads were identified by Muller (2022): (i) vehicle operation, including exhausts, leaks, leaching and wear; and (ii) road abrasion by vehicles and road maintenance work. Emissions from petrol and diesel vehicles with internal combustion engines were identified as sources of solids, PAHs, nitrogen oxides (NOx), carbon monoxide, sulphur dioxide, and Ni. In addition, vehicles powered by internal combustion engines are usually equipped with catalytic converters, which were identified as sources of Pt, Pd, and Rh. Leaks of automotive fluids such as oils and fuels, were identified as the most important source of PAHs from traffic. Leakage and vehicle wear can also add a wide array of chemicals to the road environment that may subsequently enter runoff, and tyre and brake wear were identified as primary sources of pollution. Among the main pollutants associated with tyre wear are Zn and microplastics, while brake wear mainly releases Cu and other metals including Zn, Ni, Sb and Pb.

In recent years, more research has been done on emerging substances in runoff vehicle related surfaces. For example, recently it has been found that N-(1,3-Dimethylbutyl)-N′-phenyl-p-phenylenediamine-quinone (6PPD-quinone), a transformation product of the rubber tire antioxidant 6PPD, is the chemical responsible for urban runoff mortality syndrome in coho salmon, with a median lethal concentration (LC50) of <0.1 µg/L (Tian et al., 2022). Because of the mass production and wide use of rubber-related products, 6PPD and 6PPD-quinone have been identified to be ubiquitous in the environment (Chen et al., 2023). PPD and 6PPD-quinone have also be detected in runoff water (Tian et al., 2022, Seiwert et al, 2022)

Gasperi et al. (2022) analyzed runoff from four sites with contrasting traffic levels for a very broad spectrum of molecules and elements. Sites with the highest traffic density exhibited the highest concentrations for the 'classical' substances like PAHs, some traffic-related metals, alkylphenols and phthalates. High phthalate concentration in runoff from areas with heavy traffic might be explained by the use of plastisols with high phthalate content as protective undercoating of vehicles (9% of phthalate production in western Europe) (Wicke et al., 2021). Next to these substances they found a series of emerging substances like benzotriazoles, hexabromocyclododecane (HBCD), polybrominated biphenyl ethers (PBDE) and perfluorinated compounds (PFAS). Depending on the hydrophobicity of the substance, the organic pollutants were dominantly found in the dissolved and particulate phases or in sediment (Figure 17).

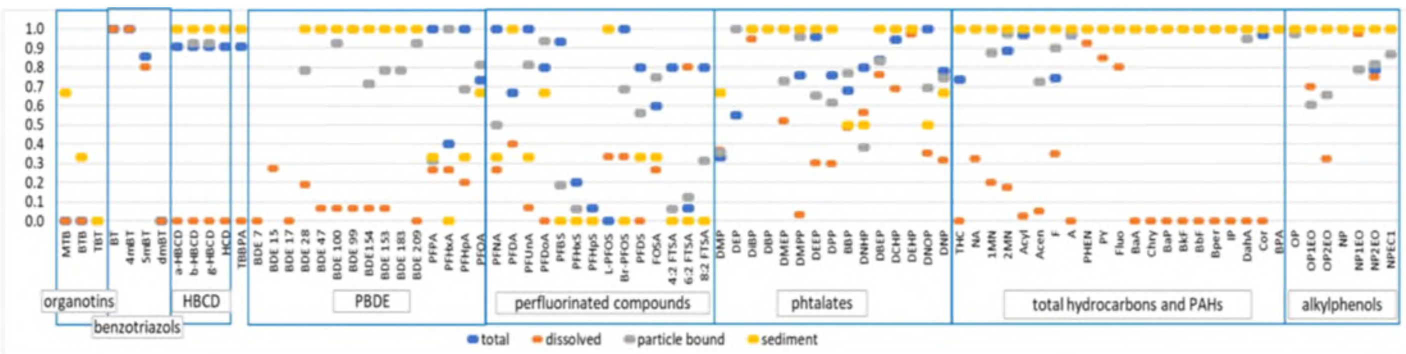

Figure 17: Quantification frequency (y-axis, in a fraction of the collected samples) of the targeted organic pollutants in the dissolved phase, particulate-bound phase and sediment in road and parking lot runoff from four sites with contrasting traffic levels situated within the Paris metropolitan area (France) (Gasperi et al. 2022)

PFASs were found ubiquitous in the work of Gasperi et al. (2022), with concentrations of individual compounds in the range of <LQ to 125 ng/L. In most samples, the PFAS molecular pattern is dominated by PFOA, followed by 6:2 FTSA, PFOS and long-chain carboxylic acids, albeit at low levels. PFASs, both carboxylic acids and sulfonates, have been detected in automotive grease and other parts of automobiles, including seats, steering systems, suspension and brakes. For example, Zhu & Kannan (2020) analyzed the occurrence of PFASs in automotive lubricants. They measured the concentrations and profiles of 13 perfluoroalkyl acids (PFAAs), encompassing nine perfluoroalkyl carboxylic acids (PFCAs; C4–C12) and four perfluoroalkyl sulfonic acids (PFSAs; C4–C10), in 18 automotive lubricants (hydraulic fluids, engine oils and grease) purchased in the United States. An interesting aspect of this study is that the lubricant extracts were analyzed before and after oxidization, to measure PFAAs and their precursors, using the total oxidizable precursor (TOP) assay. Following oxidation, lubricant extracts yielded ∑PFAA concentrations up to two orders of magnitude higher (range: 196–8300 ng/g; mean: 1840 ng/g) than those measured prior to oxidation (5.96–344 ng/g; 71.6 ng/g), which suggested the presence of notable amounts of PFAA precursors. Long-chain PFCAs (C8–C12; ∼70% of total) were the major PFASs detected (prior to oxidation). The mean molar increase in concentration upon oxidation in the TOP assay varied considerably between PFAS with different chain length. This observation suggests the need for application of TOP assay for PFAS analysis in runoff water. The results of the TOP assays as found in Zhu & Kannan (2020) are not surprising, when the Global Automotive Declarable Substance List (GADSL) is taken into account (GADSL, 2018). This is a list prepared by the Global Automotive Stakeholder Group (GASG) of both declarable and forbidden chemical substances that are expected to be present in a material or part that remains in the vehicle or part at point of sale. This list consists of 274 substance groups and a total of 6240 individual substances. The PFAS group contains 2943 individual substances, almost half of the total amount of substances. Organophosphate esters (OPEs) are widely used around the world as flame retardants, plasticizers and lubricants with a growing production in the last 15 years due to the phase-out of polybrominated diphenyl ethers.

3.2.2.2. Open urban areas

Intentional and unintentional littering and household waste disposal can be a source of contamination of runoff water in open urban areas. The most important aspect of this type of contamination is likely the fragmentation and degradation of e.g., plastic litter (bottles, bags used for collecting pet droppings, and others) as a source of microplastics (Muller et al. 2020). In addition, common plastic additives that were found to be released from plastic litter include many micro-organic pollutants, such as phthalates, BPA and polybrominated diphenyl ethers (PBDEs), and metals, that are often used as or in colourings. Moreover, littering by disposing cigarette butts in the urban environment was considered a relevant threat to urban water quality, considering their rapid release of nicotine (Muller et al., 2020)

A source of contamination in urban areas that has not gotten much attention so far is the use of veterinary medicines for treatment of domestic animals against parasites. Endo- and ectoparasites are a persistent issue with pet dogs and consequently dogs are commonly treated with veterinary parasiticides. Commonly used product application methods are oral, spot-on and collars, containing a wide variety of active ingredients. For example: collars may contain active ingredients such as deltamethrin, flumethrine, imidacloprid, diazinon or dimpylate; spot-on products may contain fipronil, imidacloprid, permethrin or piryproxyfen; and products administered by oral application include fluralaner, sarolaner, afoxolaner or spinosad (Diepens et al., 2023). ‘Run-off’ from treated pets in rainstorms or from wild swimming, as well as urine and feces and the gradual shedding of hair, are transfer pathways into the natural environment (Figure 18) that have the capacity to bypass wastewater treatments (Diepens et al., 2023; Preston-Allen et al., 2023). Recently, the Water Board Friesland found alarming concentrations of the same insecticides in the effluent of sewage treatment plants. They also concluded that the origin of these products had to be sought in veterinary medicines (Wetterskip Fryslân, 2023). They write 'Pet medicines are continuously and in many cases in standard exceeding concentration present in the effluent of all investigated WWTPs. On average, Fipronil and Imidacloprid are discharged via the effluents all the time at 120 and 4 times above the standard respectively (based on average concentrations) on the receiving water system'.

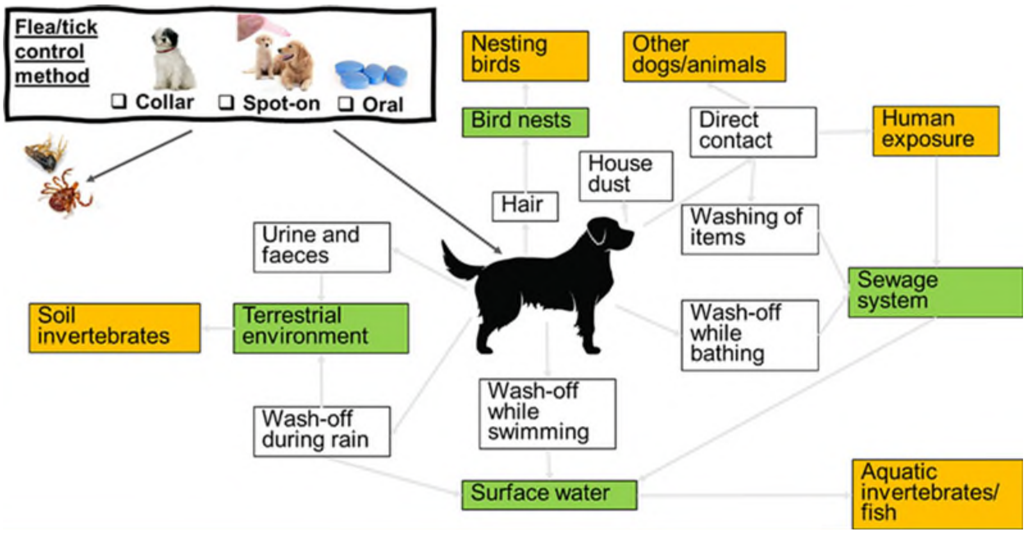

Figure 18: Transfer routes of pet dogs veterinary medicines to the environment (Diepens et al., 2023)

Recently, a study has been published in which dandelions were sampled in 15 public parks in the Netherlands to examine the presence of pesticides, biocides, anti-parasitic products for pets and a number of metabolites/transformation products of these substances (Mantingh and Buijs, 2023). The authors found 9 insecticides (including metabolites/transformation products) that used as veterinary medicines to combat fleas, ticks or lice in dogs and cats. These substances are not authorized as plant protection agents in agriculture (Mantingh and Buijs, 2023). In 8 out of 15 parks, the dandelions were contaminated with fipronil (and its metabolites/conversion products) at levels of 1.2 to 7.9 µg/kg d.m. Other anti-flea and tick products were imidacloprid, etofenprox, permethrin, phoxim and dinotefuran.

These anti-flea and tick substances are highly toxic to aquatic live and insects. As example, imidacloprid that belongs to the group of neonicotinoids, is an active ingredient in 78 products that are currently authorized in the Netherlands as veterinary medicine for treatment against fleas, ticks and lice. This substance is so potent that in theory, one monthly flea treatment for a large dog contains enough pesticide to kill 25 million bees, if applied directly (Little and Boxall, 2020). When comparing a dose of imidacloprid on an average dog of 10-20 kg (250 mg/dog) with the Dutch environmental quality standard for surface water (0,00007 µg/L) this can contaminate more than 30 thousand m^3 water which equals 12 olympic swimming pools (Mantingh and Buijs, 2023). For Fipronil this number is even higher: one dose for an average dog can contaminate almost 2 million m^3 water.

Numbers from the UK in the study of Preston-Allen et al. (2023) shows the importance of veterinary parasiticides as an environmental threat. By weight, imidacloprid is one of the best-selling veterinary parasiticides in the UK. Immediately before the ban on crop use, a combined total of over 4000 kg was used for agriculture and sold for veterinary use in a single year in the UK. After the chemical was fully banned for all outdoor use in 2018 this dropped markedly, but over 2500 kg was still being sold in the following year, all of which was destined for the domestic pet market as a parasiticide (Figure 19).

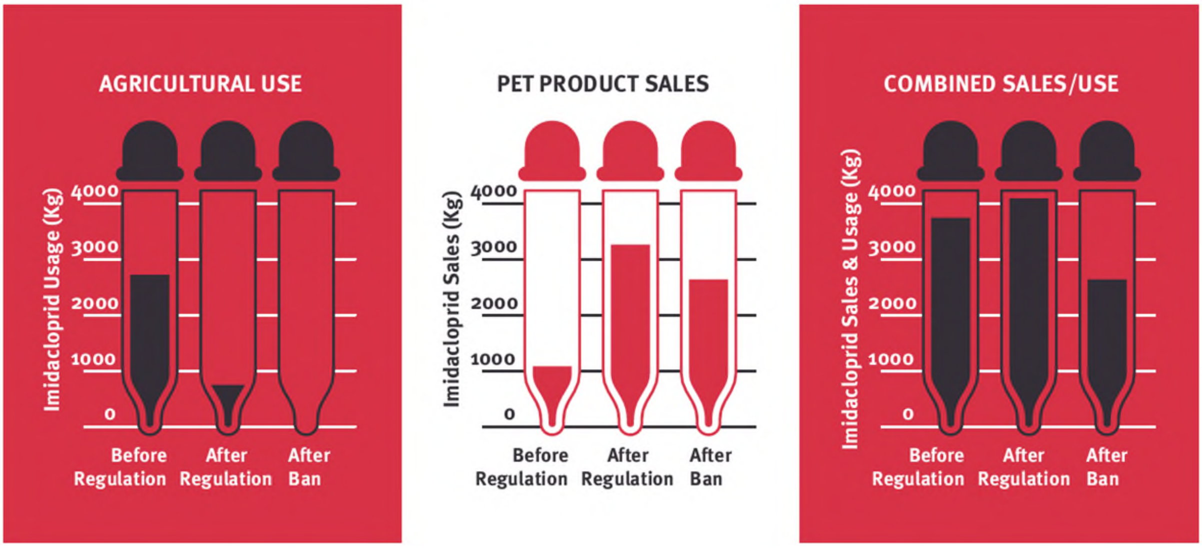

Figure 19: Patterns of the sales and usage of imidacloprid for agricultural and domestic pet parasiticide products in the UK. Imidacloprid was implicated in the global decline of bees and other terrestrial pollinators, and use was severely restricted in the EU in 2013, followed by a total ban on outdoor use in 2018. This figure shows the usage and sales of imidacloprid before (2009) and after the initial regulations (2014), as well as after the ban (2019) (Preston-Allen et al., 2023).

3.2.3 Fate of contaminants in stormwater during soil passage

As described in the previous paragraph urban stormwater runoff is often contaminated with heavy metals, polycyclic aromatic hydrocarbons and emerging pollutants such as pesticides and more specifically biocides from building materials and domestic animals, personal care products, and industrial chemicals such as PFAS that are applied in vehicles. When applied in MAR (Managed Aquifer Recharge) systems, the rapid infiltration of stormwater runoff and bypass of soil layers increases the risks of aquifer contamination. In this paragraph we present a literature overview on the fate of pollutants during soil passage. The risk of aquifer contamination depends strongly on the chemical properties of the compound in terms of persistent and mobility, see textbox below. This is because persistent and mobile substances are, as the name implies, poorly degraded in the environment after emissions (persistent) and can be transported efficiently in aquatic systems and the subsurface (mobile) (Arp & Hale, 2022; Narain-Ford et al., 2022). Due to the low mobility for hydrophobic contaminants such as PAHs and PCBs, the upper layer of soil and the unsaturated zone could act as efficient filters, with a minor risk of leaching for these chemicals (e.g., Pinasseau et al., 2020). However, this retention efficiency of the soil and unsaturated zone is less effective for more hydrophilic emerging contaminants such as pesticides, industrial chemicals and personal care products and that may be present in stormwater runoff.

MAR systems where water is infiltrating through a vadose zone into a saturated aquifer, can also achieve enhanced contaminant removal via biodegradation, next to sorption mechanisms (Filter et al., 2021). This also applies for MAR systems where water infiltrates through riverbank filtration or basin infiltration thus without an unsaturated zone and where redox conditions are more anoxic (e.g., Hamann et al., 2014). The redox conditions, concentration and composition of dissolved and particulate organic carbon (DOC/POC), subsurface material composition, nutrient availability and hydraulic retention times (HRT) are often considered crucial parameters in the biological transformation of organic micropollutants during infiltration (Van der Grift et al., 2022, Ma, et al., 2023, Filter et al., 2021). In many cases, incomplete degradation of organic contaminants leads to the formation of transformation products, whose molecular structure, physicochemical properties, toxicity, and environmental behavior is often unknown. Hensen et al. (2018) found transformation products of facade biocides Diuron, Terbutryn and Octylisothiazolinone in groundwater that is under influence of stormwater infiltration systems.

Filter et al. (2021) collected peer-reviewed literature published between 2010 and 2018 on removal of organic micropollutants from treated wastewater and impacted surface water through managed aquifer recharge (MAR) (Figure 21). The group of well-studied compounds (N_{exp} > 8) consist mostly of pharmaceuticals who are not of primary concern in stormwater runoff, but the results of this study are interesting. In this group there are compounds showing consistent removal efficiency in most studies (standard deviation < 30%) with a persistent behaviour (e.g., bisphenol A, atrazine, carbamazepine, primidone, or tramadol) and efficient removal (e.g., diphenhydramine, atenolol, naproxen, trimethoprim) in MAR systems. However, their literature results show a large group of well-studied compounds with large discrepancies in reported removal percentages. A standard deviation in reported removal percentages above 30% was observed for 24 of the 49 most studied substances. Such variations suggest a rather inconsistent capacity of biologically active infiltration systems to remove these compounds that likely depends on the parameters described in the previous paragraph. Interestingly, 11 out of the 24 compounds demonstrated increased removal with increasing change in DOC concentrations during infiltration.

Although not explicitly considered in the study of Filter et al. (2021), the authors claim that adaptation and growth of the biofilm in an infiltration system is an important factor which influences quickly steady-state removal of organic contaminants. A comparable hypothesis has been formulated in Van der Grift et al., 2022. This study into the removal of organic micro-contaminants during soil passage showed that specific compounds that where persistent in the surface water where rapidly removed from the water during infiltration. The hypothesis is that redox gradients in the subsurface where subsequently nitrification and denitrification occurs and that also have a certain hydraulic residence time (thus not to steep) are favourable conditions for the degradation of organic micro-contaminants (Figure 22).

persistence and mobility

The persistence of a chemical is typically assessed based on single compartment half-lives under specified conditions that are simulated in the laboratory. Experimental derived $T_{1/2}$ values are rare. According to the study of Arp & Hale (2022) these values are only available for 2.2% of the 14.203 unique chemicals identified under REACH. There laboratory derived half-lives present a simplification of the natural variability of the real world. In the subsurface, half-lives are dependent on temperature, redox conditions, nutrient loads, pH, microbial community and the (mineral) composition of the soil. Because of all these factors that may influence the degradation it is difficult to predict the half-live of organic contaminant. For example, 1-2 orders of magnitude differences in biodegradation rate constants under oxic conditions are observed between batch, column, and field-scale experiments (Greskowiak et al., 2017). This indicates that half-live values should ideally be assessed from field studies.

The mobility of a chemical compound in soils is generally quantified using equilibrium distribution coefficients that are normalized to the mass fraction of organic carbon, the K_{OC} approach. Standardized methods to determine equilibrium K_{OC} at defined conditions have been developed. The uncertainty in addressing the mobility by this K_{OC} approach can be particularly large in the case of charged and ionizable compounds, where sorption is not only dependent on the organic carbon content but also on the concentration of contamination (nonlinear sorption) and on fluctuations in pH that affect the ionizability of the compound and the soil. Alternative approaches to better assess the mobility of charged and ionizable compounds should be developed and implications on their regulation and risk assessment should be discussed (Sigmund et al., 2022). The development of better models for mobility of this growing class of chemicals needs consistent and reliable sorption measurements at well-defined chemical conditions in natural porewater, better compound and sorbent characterization. Such models should be complemented by monitoring data from the natural environment.

3.2.4 Pretreatment of stormwater

Stormwater runoff results in substantial emission of pollutants to surface water. From the nineties onward systems were put in place to reduce these emissions in the Netherlands (Langeveld et al., 2016). These systems focus on settling or filtration of suspended particles (TSS) based on the traditional notion that a large part of the heavy metal, nutrient and PAH pollutant load is bound to particles. Several systems varying from simple settling ponds to high-rate sand filters, lamella settlers and soil filters/constructed wetlands are since installed. In a comparative study by Langeveld et al. (2012), lamella filters proved less effective in removal of TSS (34%) compared to high-rate sand filtration (75%) and soil filtration (70%). This was probably caused by the design guidelines used for the lamella filter which proved inappropriate for the Dutch stormwater characteristics (Langeveld et al., 2016). The removal rates of the soil filter for TSS, nutrients and heavy metals are in accordance with rates reported in literature, such as the BMP reports of the Daywater project (Rombout et al., 2007). The sand filter shows lower removal rates than the soil filter, and much lower for instance Copper (17 vs 81%), which might be explained by a lack of binding capacity of the sand applied in the sand filter. The removal efficiencies reflect the dominant removal processes in the setups: just settling for the lamella filter, filtration for the high-rate sand filter and soil filter and possibly sorption for the soil filter (Langeveld et al., 2012). Overall, the removal efficiencies obtained reflect the dominant removal processes. The removal of pollutants in the lamella settler is based on settling, whereas the sand and soil filters rely on filtration and the soil filter additionally on possible adsorption of pollutants.

The need for pretreatment became even more important with a shift from discharge of stormwater to surface water towards infiltration of stormwater using infiltration drains, boxes and even injection wells. These infiltration systems are sensitive for clogging and sometimes hard to regenerate when clogged (Siriwardene et al., 2007). In the past years, several Dutch municipalities noticed that their infiltration systems start to clog with suspended solids in the stormwater. The municipality of Apeldoorn now installs prefiltration systems (rapid sand filtration) to effectively prevent clogging of deep well infiltration systems (Figure 20). Another example of pretreatment (using a biofilter) is investigated in Rotterdam (Zuurbier & Van Dooren, 2019). Results from these locations confirm reduction of heavy metals, PAH and glyphosate/AMPA with varying efficiency. Research on removal of other substances than heavy metals, nutrients, PAHs and mineral oil by prefiltration systems however is scarce and not included in the above-mentioned studies. Only recently papers on the application of different filter systems such as constructed wetlands and stormwater biofilters for treatment of micro-pollutants in stormwater start to appear, although PAHs have been of more interest, and emerging OMPs such as phenolic substances have been largely ignored, despite their potential environmental risks (Beryani, 2023; Beryani et al., 2023). Conventional stormwater biofilters are based on sandy engineered soils with low organic matter content. These soils have often limited treatment capacities for removal of dissolved fractions of heavy metals and nutrients (Tirpak et al., 2021). To improve removal efficiency, several additional materials have been tested including, chalk, biochar, zeolite, fungi, and iron (hydr)oxides (Witteveen+Bos & VMM, 2019; Van den Bulk et al., 2022; Beryani, 2023; Bentley & Summers, 2020). Van den Bulk et al. (2022) compared six approaches for treatment of organic micropollutants in WWTP-effluent on removal efficiency, costs, TRL, land claim and several other criteria. Traditional systems (e.g. vertical and horizontal flow helophyte filters and aerated LECO-filters) were not able to reach the goal of 70% removal of 7 guideline organic substances. More innovative systems such as vertical flow filters systems with fungi and/or adsorbentia such as zeolites and biochars show promising results but still have low TRL levels.

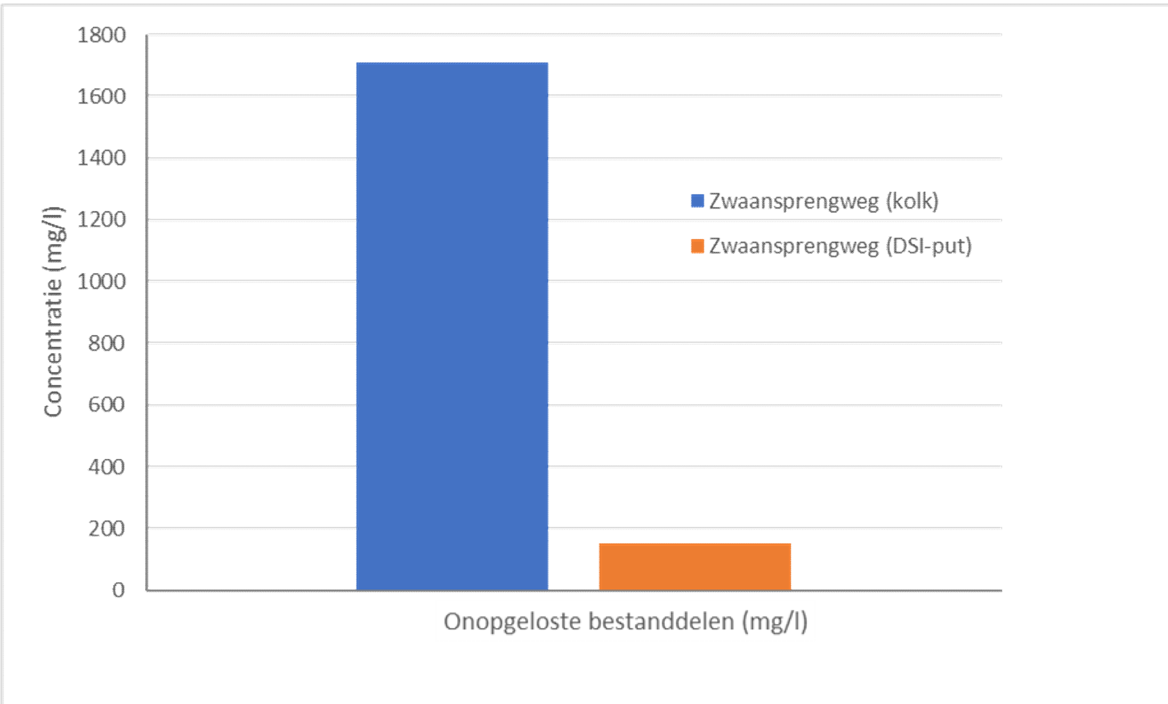

Figure 20: Example of removal of suspended solids using a 'HWZI' high-rate sand filtration system (source: municipality of Apeldoorn). With blue the concentration suspended solids before and orange the concentration after pretreatment.

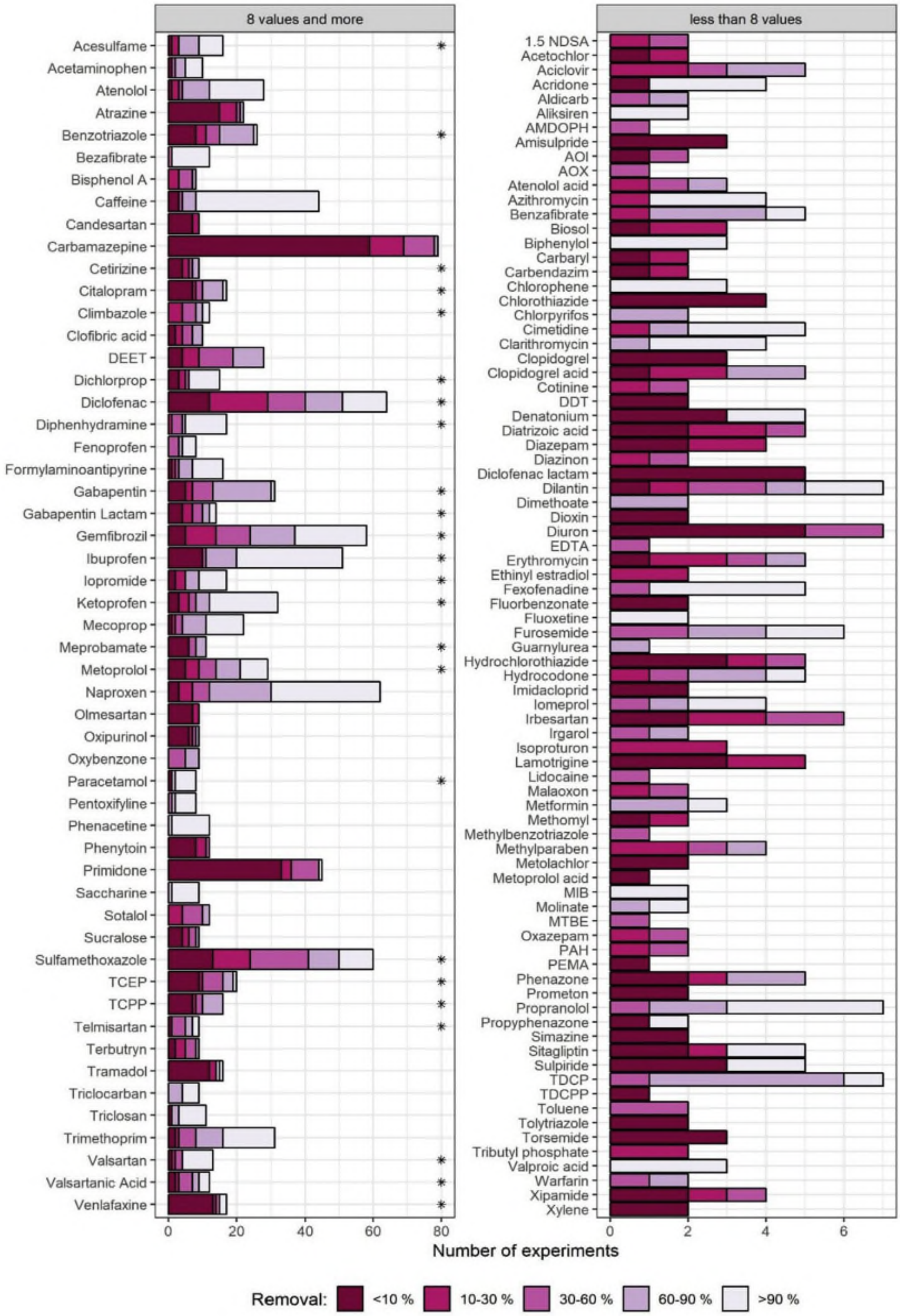

Figure 21: Removal percentage for organic compounds observed in biologically active filtration systems reported in peer-reviewed literature with more commonly studied compounds depicted in the left column (Nexp > 8) and less commonly studied compounds in the right column. The star (*) denotes compounds for which the standard deviation in removals was above 30% (Filter et al., 2021)

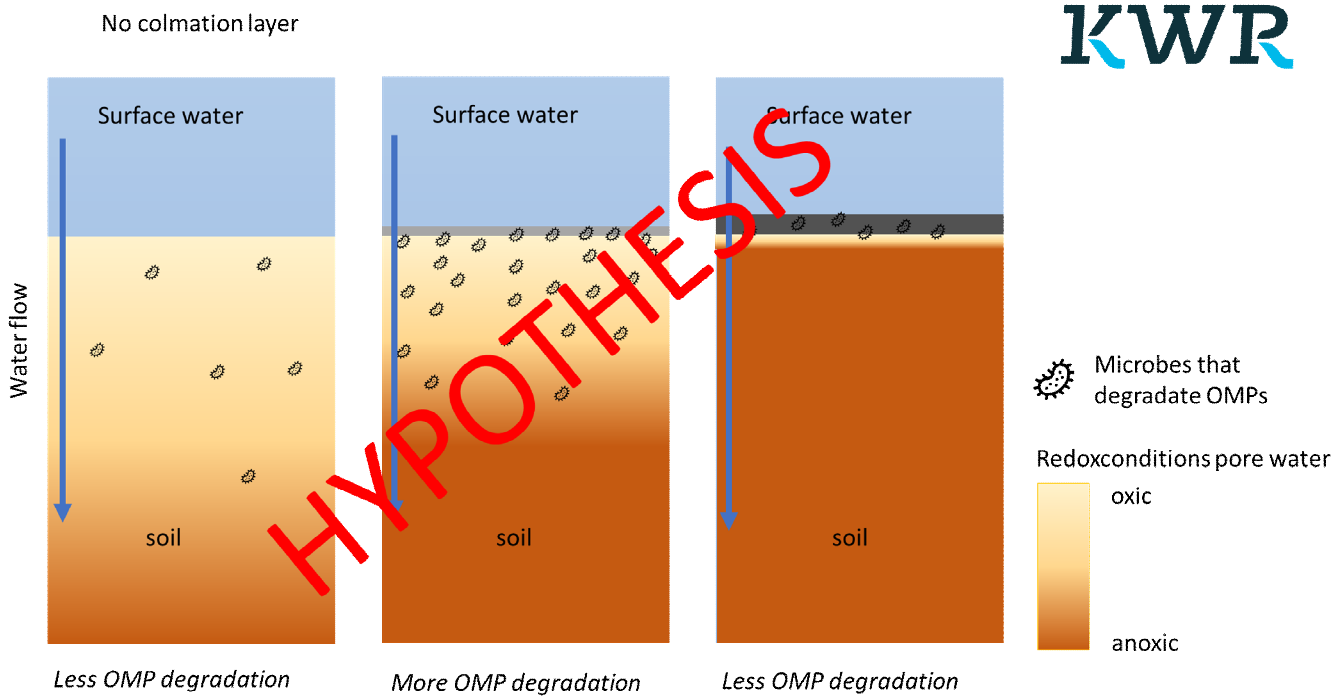

Figure 22: Possible impact of a colmation layer on the redox gradient and the presence of specific microbial groups in infiltration systems that controls the degradation of organic micropollutants (OMP) (Van der Grift, 2022) .

4 Conclusions & recommendations

4.1 Conclusions on stormwater infiltration impacts on groundwater quantity and literature review on stormwater quality impacts

This report presents a first insight into potential quantitative impacts of stormwater infiltration on groundwater resources in drinking water protection zones. Secondly, an assessment of the qualitative considerations of stormwater infiltration has been carried out based on a literature review.
The quantitative assessment is based on a GIS analysis to quantify the potential of stormwater infiltration for additional groundwater recharge. This tool quantifies the water quantity aspect in a decision-making process to weigh out water quantity-quality aspects of infiltration practices and to assess if stormwater infiltration can significantly increase groundwater recharge. The obtained potential map shows a high potential of stormwater availability for infiltration and MAR applications, given the high urbanization levels associated with impermeable surfaces in a series of Flemish protection zones. Especially zones around the city of Leuven show high stormwater infiltration potential. In these areas, groundwater recharge can potentially be doubled if all stormwater could recharge the aquifer. Furthermore, yearly pumping volumes can be compensated by these stormwater volumes. Other protection zones show lower, but significant stormwater volumes for additional groundwater recharge.
The focus on stormwater quality was traditionally strongly oriented on nutrients, heavy metals, bacteria, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). Groundwater quality issues for these 'traditional' contaminants caused by infiltration of stormwater with MAR systems are relatively limited due to the strong hydrophobic nature of most of these compounds. Limited research has shown that stormwater may contain emerging contaminants such as pesticides (e.g. Glyphosphate, Mecoprop-P, Diuron, Imidacloprid), personal care products (e.g., DEET), industrial pollutants such as per- and polyfluoroalkyl substances (PFAS), benzotriazoles, alkyphenol surfactants, phthalates and flame retardants (pentachloorbenzene and trichloorpropylfosfaat) and tire wear particles and compounds (6PPD and 6PPD-quinone).
The presence of these emerging contaminants in stormwater are of great concern due to their persistence and mobility in combination with their toxic properties. Much is still unknown regarding the effects of stormwater infiltration on groundwater quality issues related to these emerging contaminants. Two aspects are important here. First, the biodegradation potential of many organic micropollutants during infiltration in natural and engineered systems is still unclear or unknown and incomplete mineralisation results in the formation of transformation products whose molecular structure, physicochemical properties, toxicity, and environmental behavior is often unknown. This is due to the complexity of factors that may control the biodegradation rate. The redox conditions, subsurface material composition, nutrient and DOC availability and hydraulic retention times (HRT) are often considered as crucial parameters in the biological transformation of organic micropollutants during infiltration. Second, the assessment of the mobility of organic micropollutant in the subsurface are commonly based on the classical K_{OC} approach that accounts only for hydrophobic sorption mechanisms. This approach is insufficient for the growing group of charged and ionized emerging contaminants for which electrostatic interactions with charged soil constituents play a critical role as well.
Stormwater infiltration requires some kind of pretreatment to remove suspended particles (TSS) because infiltration systems are sensitive for clogging and sometimes hard to regenerate when clogged. Based on the traditional notion that a large part of the heavy metal, nutrient and PAH pollutant load is bound to particles this kind of pretreatment systems also reduce the emission of these compounds. Research on the removal efficiency by prefiltration systems and soil passage for these compounds is however limited and with regard to emerging contaminants almost absent.

Currently, there is insufficient understanding of the presence of emerging charged and ionized substances in stormwater runoff to indicate the risk of groundwater contamination. In addition, it is not clear to what extent these substances are removed from stormwater during pre-treatment or during actual infiltration and transport through the soil. This requires additional research into the removal efficiency of these compounds and the biogeochemical mechanisms behind this.

4.2 Recommendations

The potential map for stormwater infiltration shows high potential for the use of stormwater as source of MAR applications. Following recommendations can be made:

- Allowing stormwater infiltration and MAR practices in all protection zones is beneficial from a quantitative perspective, given the high urbanization level of Flanders.
- Highest stormwater infiltration potentials are noticeable in protection zones around the city of Leuven. In these urban areas, stormwater infiltration can have the biggest impacts. Additionally, infiltration in this urban setting is beneficial as natural groundwater recharge has declined in these areas due to urban expansion and associated increases in imperviousness (Zomlot et al., 2017).
- However recent studies (e.g. Gasperi et al., 2022; Muller, 2022; Wicke et al., 2021; Masoner et al., 2019; Langeveld et al., 2020) raise concern on the occurrence of emerging contaminants in stormwater. Research is needed on the quality of stormwater from impermeable surfaces, especially with regards to emerging contaminants (e.g., pesticides, industrial pollutant, PFAS, …) in the Flemish and Dutch setting.
- Additional insights regarding the natural treatment capacity of soils due to processes such as biodegradation and sorption are needed to understand the actual risk of groundwater contamination from stormwater infiltration practices. This is especially for emerging charged and ionizable organic compounds
- New approaches to better assess the mobility of charged and ionizable organic compounds in soils should be developed.
- Given the knowledge gap on the presence of emerging contaminants in stormwater and the behaviour of these compounds during soil transport it is advisable to be reluctant to large scale infiltration of stormwater in groundwater abstraction area's.

4.3 Further research

To further assess quantitative impacts of stormwater infiltration on groundwater resources, future research taking into account measured groundwater levels and groundwater modelling tools will help to gain an insight into the impact of stormwater infiltration on groundwater dynamics (Ringleb et al., 2016). Furthermore, research is needed to identify suitable areas for infiltration and MAR sites. MAR suitability maps have been created for many areas in the world (e.g. Rahman et al., 2012; Sallwey et al., 2019), using a variety of criteria such as soil type, aquifer thickness, and depth to groundwater. A similar MAR suitability map of Flanders (and the Netherlands) would therefore increase understanding to identify suitable infiltration and MAR locations based on subsurface characteristics. Lastly, the research gap on water quality impacts of stormwater infiltration on groundwater, especially with regards to emerging contaminants, needs to be further investigated (Fairbairn et al., 2018; Pinasseau et al., 2020), to be able to assess water quality risks in this water quantity-quality balancing exercise.

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Appendix I Stormwater volumes per protection zone

Protection zone name	Protection zone size (m²)	Potential stormwater volume (m³)
Eisden-Vrietselbeek-Meeswijk	22140117	2768436
Abdij-Cadol	7090239	1500719
Berlare-Zele	16726334	1266812
Huiskens	6659715	1124685
Egenhoven	7798020	991185
As	8289871	954897.5
Avelgem-Waarmaarde-Kerkhove	11206677	821268.3
Den Dijk	6740738	637578.3
Leefdaal	7249301	633974.6
Vlierbeek	4499975	552986.8
Groot-Overlaar	6541269	530359.4
Schoonhoven-Weerderlaak	6982900	522163.4
Winksele"Kastanjebos"	7742820	509235.8
Snellegem	10745655	507632.8
Bijlokestraat	3628456	499423
Beernem	8668696	492430.9
Lembeke-Oosteeklo	14122212	474219
Lommel	8055706	455093.6
Eeklo-Kaprijke	10607873	430219.4
Puttebos	6597160	424327.6
Het Rot	4693525	372258.7
Kouterstraat-Nellebeek	5344274	363573.7
Katte-Meuterbos	8210096	348012.1
Bertem	10939166	330931.8
Vinkenberg	5161986	316691
Moerbeke-Wachtebeke	7925325	277193.1
Hoeilaart	2500386	273245.3
Klemskerke	1856224	267791.8
Scherpenheuvel Put4-5	2921875	263210.8
Neerpelt	3513835	222009.4
Grobbendonk	2332267	212630
Menebeek (Kumtich)	4146755	207295.8
Brasschaat	2293044	198307.3
Beerse	569519	189535.5
Londerzeel	4230796	166757
Venusberg	3731316	157576.2

Voort	4274930	157397.6
Kapellen	1520490	138016.1
Smalle Rijt	1369082	127708.8
Essen	3603410	96170.92
Haanheuvel	1482271	80325.19
Bovelingen-Rukkelingen-Loon	3059094	76633.37
Lauw-Tongeren	2714044	72491.94
Veeweyde	1125976	64007.99
Diets-Heur	3580215	59209
de Wamp Oud-Turnhout	1795387	42571.46
Olen	837993	40776.13
Hoogstraten	1208419	37512.07
Trekschuren	225980	35707.99
Vorst	2443986	34190.55
Balen-Kanaal	1590106	30144.66
Herselt	1746299	26004.48
Bolkse Heide	1389944	23736.43
Zeven Bronnen	2008276	18785.07
Zoutleeuw	274546	17985.13
Wuustwezel	2092791	16999.11
Velm	1833187	13634.51
Meerle	2037884	11925.35
Poederlee	1512142	11453.26
Tombeek "Sana"	295992	8522.035
Heusden-Zolder	56320	7253.128
St-Andra	1262500	7246.883
Ravels	2713546	5814.367
Vliermaal	52962	4609.155
Ronse	133921	4527.351
Knokke-Heist	17632	3822.333
Hasselt	16256	3654.352
Zaventem	36408	3377.716
Spiere	29292	2760.747
Mol	545811	1818.434
Oudenaarde	348304	1778.468
Nieuwerkerken	6508	1612.986
Waltwilder	74478	1491.84
Geuzenhoek	28049	1205.836
Opitterkiezel	5191	1163.373
Schijtenroot	42821	979.1566
Oostmalle	131005	949.8069
Wintershoven	15355	848.6441
Bisschoppen	1177715	640.6982
Zepperen	21655	633.8291

Vilvoorde	1281	502.692
Balen-Nete	1460643	463.3509
Vlakenhof Maaseik-Kinrooi	17836	168.6048
Kooigem-WPC Spiere-Helkijn	261	111.7787
Ronsemeersstraat	0	74.93546
Puttestraat	2361	39.96558
Heerbaan	5206	1.873386
Kloosterweg-Beukenbosstraat	2601	0

Appendix II Percentage stormwater volume versus current groundwater recharge for Flemish protection zones

Protection zone name	Protection zone size (m²)	Comparison potential stormwater volumes versus current groundwater recharge (%)
Vilvoorde	1281	412.6899
Kooigem-WPC Spiere-Helkijn	261	295.8755
Knokke-Heist	17632	155.8537
Nieuwerkerken	6508	146.2219
Beerse	569519	126.4741
Abdij-Cadol	7090239	112.386
Hasselt	16256	102.9138
Huiskens	6659715	86.36125
Opitterkiezel	5191	84.29026
Klemskerke	1856224	81.93637
Trekschuren	225980	81.67324
Bijlokestraat	3628456	71.77195
Egenhoven	7798020	68.83363
Eisden-Vrietselbeek-Meeswijk	22140117	56.98028
Spiere	29292	56.08431
Vlierbeek	4499975	55.25185
Groot-Overlaar	6541269	50.28697
Hoeilaart	2500386	48.81652
Vliermaal	52962	45.44364
Heusden-Zolder	56320	44.96005
Leefdaal	7249301	44.60335
Den Dijk	6740738	44.4102
As	8289871	41.19312
Zaventem	36408	40.67625
Smalle Rijt	1369082	36.0129
Scherpenheuvel Put4-5	2921875	35.89394
Schoonhoven-Weerderlaak	6982900	35.38476
Wintershoven	15355	35.17658
Avelgem-Waarmaarde-Kerkhove	11206677	34.8769
Grobbendonk	2332267	31.60137
Kouterstraat-Nellebeek	5344274	31.4591
Het Rot	4693525	31.2364
Berlare-Zele	16726334	30.88355
Winksele"Kastanjebos"	7742820	30.44418

Puttebos	6597160	30.21288
Zoutleeuw	274546	30.20779
Menebeek (Kumtich)	4146755	28.75066
Veeweyde	1125976	27.32447
Kapellen	1520490	26.70981
Vinkenberg	5161986	25.6884
Brasschaat	2293044	25.23175
Geuzenhoek	28049	22.72063
Neerpelt	3513835	20.66853
Haanheuvel	1482271	19.77546
Beernem	8668696	19.64711
Lommel	8055706	19.60649
Voort	4274930	18.51762
Snellegem	10745655	18.14145
Ronse	133921	18.07773
Katte-Meuterbos	8210096	17.85996
Venusberg	3731316	17.65128
Olen	837993	16.9878
Zepperen	21655	15.31704
Bertem	10939166	14.68291
Londerzeel	4230796	14.48142
Eeklo-Kaprijke	10607873	13.05268
Schijtenroot	42821	12.40434
Bovelingen-Rukkelingen-Loon	3059094	11.74477
Moerbeke-Wachtebeke	7925325	11.65139
Lembeke-Oosteeklo	14122212	11.2104
Lauw-Tongeren	2714044	10.97868
Tombeek "Sana"	295992	10.60668
Hoogstraten	1208419	8.884401
Waltwilder	74478	7.815558
Puttestraat	2361	7.713335
Essen	3603410	7.293464
de Wamp Oud-Turnhout	1795387	7.120597
Balen-Kanaal	1590106	6.565837
Diets-Heur	3580215	6.557474
Herselt	1746299	5.563842
Vorst	2443986	5.362814
Bolkse Heide	1389944	5.036253
Zeven Bronnen	2008276	4.540263
Velm	1833187	3.994201
Vlakenhof Maaseik-Kinrooi	17836	3.41997
Oudenaarde	348304	2.525642
Poederlee	1512142	2.491402
St-Andra	1262500	2.144886

Wuustwezel	2092791	2.00844
Oostmalle	131005	2.007366
Meerle	2037884	1.666351
Mol	545811	1.087199
Ravels	2713546	0.627216
Ronsemeersstraat	0	0.606984
Heerbaan	5206	0.174484
Bisschoppen	1177715	0.164268
Balen-Nete	1460643	0.105778
Kloosterweg-Beukenbosstraat	2601	0

Appendix III Percentage stormwater volume versus pumping volumes for Flemish protection zones of De Watergroep

Protection zone name	Protection zone size (m²)	Comparison yearly potential stormwater volumes versus pumping volumes (%)
Huiskens	6659715	123.5387
Egenhoven	7798020	119.1058
Vlierbeek	4499975	86.44106
Avelgem-Waarmaarde-Kerkhove	11206677	82.37981
Bijlokestraat	3628456	82.07269
Hoeilaart	2500386	76.36517
Berlare-Zele	16726334	71.41399
Abdij-Cadol	7090239	63.84062
As	8289871	53.17228
Winksele"Kastanjebos"	7742820	48.62145
Schoonhoven-Weerderlaak	6982900	48.35258
Kouterstraat-Nellebeek	5344274	47.56776
Lembeke-Oosteeklo	14122212	41.30371
Beernem	8668696	38.352
Snellegem	10745655	38.02832
Eeklo-Kaprijke	10607873	32.69637
Bertem	10939166	31.33979
Leefdaal	7249301	24.44553
Moerbeke-Wachtebeke	7925325	24.22297
Venusberg	3731316	18.66939
Eisden-Vrietselbeek-Meeswijk	22140117	13.89266
Diets-Heur	3580215	12.37026
Londerzeel	4230796	11.80651
Zeven Bronnen	2008276	6.186198
Velm	1833187	0.874831

Appendix IV Comparison of protection zones of De Watergroep and Pidpa

Protection zone size (m^3)	De Watergroep	Pidpa
Count	56	21
Mean	4.76 * 10^6	1.64 * 10^6
Standard deviation	4.68 * 10^6	800970
Minimum	261	131005
25%	224529	1.21 * 10^6
50%	3.94 * 10^6	1.52 * 10^6
75%	7.37 * 10^6	2.09 * 10^6
Maximum	2.21 * 10^7	3.60 * 10^6
t-test statistic	3.03	
p-value	0.003	

Impermeable land cover percentage (%)	De Watergroep	Pidpa
Count	56	21
Mean	13.64	7.41
Standard deviation	13.23	11.73
Minimum	0.06	0.05
25%	5.82	1.16
50%	10.21	3.04
75%	15.74	8.68
Maximum	68.58	53.29
t-test statistic	1.90	
p-value	0.06	