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Enhancing groundwater recharge in drinking water protection zones in Flanders (Belgium): A novel approach to assess stormwater managed aquifer recharge potential

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ABSTRACT

Study region: Flanders (Belgium)
Study focus: Stormwater infiltration for managed aquifer recharge is increasingly recognized as a drought adaptation measure. Given the high degree of urbanization and imperviousness, stormwater infiltration has significant potential in Flanders (Belgium). This research presents a novel approach to quantify stormwater availability and its potential to enhance groundwater recharge. Stormwater volumes available for recharge are calculated based on the imperviousness level, yearly average precipitation volumes, and runoff coefficients. This study focuses on groundwater protection zones around drinking water wells to assess the role of increased infiltration for sustainable drinking water production. Calculated potential stormwater volumes for recharge are compared to natural groundwater recharge and pumping volumes for drinking water production to quantify the potential significance of stormwater infiltration for aquifer recharge.
New hydrological insights for the region: Results show a high potential for stormwater infiltration in Flemish protection zones with an average of 17% (7%-33%) additional groundwater recharge from stormwater infiltration. Additionally, stormwater recharge could potentially compensate for 19% (8%-37%) of abstracted drinking water production from phreatic aquifers. Locally, higher groundwater recharge potentials were calculated, especially in protection zones around the city of Leuven. Therefore, stormwater harvesting for infiltration and groundwater recharge should be further encouraged throughout the region, with special attention to urban areas. However, further research is needed on stormwater quality to assess groundwater quality risks in this water quantity-quality balancing exercise.

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1. Introduction

Extreme weather events such as droughts and floods are expected to increase in the region of Flanders (Belgium) due to climate change, with climate models predicting 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 (2018–2020, and 2022), phreatic groundwater levels in summer have been very low for the time of the year (P10 percentile compared to the last 30 years) 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). Although tap water consumption is expected to stagnate or decrease, high peak demands are expected during future drought periods (VMM, 2019). 'Managed Aquifer Recharge' (MAR) is seen as important strategy to enhance resilience against drought and water scarcity (Dillon et al., 2009; Zhang et al., 2020). MAR intentionally increases groundwater recharge, takes advantage of the aquifer's buffering capacity to store water, and can be supplied by different water sources including surface water, treated wastewater and stormwater (Dillon et al., 2020; Escalante et al., 2019). A series of MAR types exist, including infiltration ponds and riverbank filtration recharging shallow, unconfined aquifers, whereas other practices such as aquifer storage and recovery (ASR) recharge deeper, confined aquifers through well injections (Dillon et al., 2009; Zhang et al., 2020).

Globally, stormwater is seen as a valuable water source for a range of MAR types (Angrill et al., 2017; Dillon et al., 2014). Although varying definitions exist, stormwater is here defined as urban runoff, generated from all precipitation fallen on impermeable surfaces that does not evaporate or percolate through the soil (Jegatheesan et al., 2019). Given the high degree of urbanization, the percentage of sealed surfaces in Flanders is approximately 16% (Vlaamse Overheid, 2022a). Therefore, a considerable volume of stormwater could potentially be harvested and infiltrated to enhance groundwater recharge. Consequently, stormwater MAR in Flanders is especially encouraged in the form of infiltration measures promoted through the Blue Deal, a policy plan to tackle drought and water scarcity (Integraal Waterbeleid, 2020).

However, the use of stormwater for MAR applications may be associated with water quality risks as stormwater can contain contaminants that threaten groundwater quality in addition to negative effects on the infiltration system due to potential clogging. Important contaminants include nutrients, inorganic compounds (i.e. metals and ions), organic compounds, polycyclic aromatic hydrocarbons (PAHs), 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, industrial compounds, and per- and poly-fluoroalkyl substances (PFAS) (Fairbairn et al., 2018; Pinasseau et al., 2020; Saifur and Gardner, 2021; Sánchez et al., 2015). In general, atmospheric deposition and corrosion of roofing materials are the main pollution sources for roof runoff (De Buyck et al., 2021; Gwenzi et al., 2015; Song et al., 2019). Furthermore, road stormwater pollution is related to traffic and can include PAHs due to combustion (De Buyck et al., 2021; Pramanik et al., 2020), microplastics originating from car tires (Pramanik et al., 2020; Wagner et al., 2018) and emerging contaminants used in vehicles (Gasperi et al., 2022).

Historically, stormwater infiltration in protection zones around Flemish groundwater abstraction wells for drinking water production has therefore been prohibited to prevent groundwater contamination. However, given the increased focus on infiltration as a drought adaptation measure to counter water scarcity risks, new policy guidelines have removed this restriction (Vlaamse Overheid, 2023, 2013), 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 both 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.

Quantification of stormwater volumes and their potential impacts on groundwater recharge is therefore essential. Rainwater harvesting volumes are traditionally quantified for urban drainage and flood protection purposes. Several methods of stormwater quantification exist, ranging from the rational method to more complex modelling approaches (American Society of Civil Engineers, 1993; Urban Drainage and Flood Control District, 2018). The rational method, used in this study, estimates stormwater volumes by multiplying the impervious surface area with the precipitation over this area. Then, this volume is multiplied by a runoff coefficient to account for processes such as evaporation, infiltration through surface materials, and initial surface wetting (American Society of Civil Engineers, 1993; Angrill et al., 2017; Farreny et al., 2011).

However, less is known about the impact of stormwater infiltration on the groundwater system. Although the positive effect on groundwater availability is acknowledged, quantifying the impact of stormwater MAR practices on the groundwater system is a challenging task (Glendenning et al., 2012). Studies often use modelling tools to investigate the MAR 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, concluding that MAR projects would reduce seawater intrusion. Similarly in California's Central Valley, Alam et al. (2020) estimated a potential compensation of 9 – 22% of the groundwater withdrawal by MAR applications based on a coupled surface water-groundwater model. Specifically for MAR systems supplied by stormwater, several studies reported a (local) rise of the water table, for example up to 1.1 m for bioretention basins in a case study in Syracuse (US) (Endreny and Collins, 2009) and up to 1.5 m in Maryland (US) (Bhaskar et al., 2018).

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 to identify high-potential regions. Therefore, this research proposes a novel approach based on a Geographical Information System (GIS) analysis to quantify the stormwater potential for aquifer recharge enhancement. Using meteorological, land cover, groundwater recharge, and abstraction data, the method aims to quantify the potential additional groundwater recharge from stormwater infiltration. This method calculates the impact of the following what-if scenario: "What if all stormwater from sealed surfaces in protection zones is used for infiltration instead of discharged into the sewer system?" The analysis can be used as a screening evaluation to assess which areas have the highest stormwater potential for groundwater recharge. This paper applies this novel method to all drinking water protection zones in Flanders. The additional recharge volume due to stormwater infiltration originating from impermeable surfaces is compared to current groundwater recharge and pumping rates in protection zones to assess its potential significance and to answer the question: "What are the potential impacts of stormwater infiltration on groundwater recharge volumes in groundwater protection zones in Flanders?". This screening tool can be used by decision makers and stakeholders such as drinking water companies to assess which areas should be prioritized for stormwater MAR implementation.

2. Data and methods

2.1. Groundwater and groundwater protection zones in Flanders, Belgium

Flanders (Northern region of Belgium) is dependent on groundwater for various purposes. Half of Flemish drinking water is produced from groundwater (VMM, 2020), and agriculture and industry take up respectively 20% and 12% of total groundwater usage (VMM, 2020). Additionally, 90% of Flemish nature reserves consist of groundwater-dependent vegetation and habitats (De Becker, 2020), and research indicates drought impacts on these nature reserves through changes in groundwater discharge (Wossenyeleh et al., 2021). Simultaneously, Flanders is a highly urbanized area with 492 inhabitants per km^2 (Statbel, 2022). Since the 1970 s, the region has experienced a so-called 'urban sprawl', characterized by a conversion of arable and grasslands to urban areas and urbanization occurring throughout the region (De Decker, 2011; Poelmans and Van Rompaey, 2009). Continuous urbanization has led to a high percentage of land sealing, which decreases infiltration and groundwater recharge. The Copernicus Programme (2018) ranks Belgium within the top 3 most sealed European countries with approximately 8% of impermeable land surfaces. Furthermore, it is estimated that the region of Flanders within Belgium consists of 16% land sealing (Vlaamse Overheid, 2022a).

Given the importance of groundwater for drinking water production, zones around drinking water production wells have been established between 1985 and 1995 based on groundwater travel times to safeguard groundwater quality (Fig. 1). These zones consist of three levels. Type 1 is the closest area around the well, in which recharged water reaches the groundwater well in less than 24 hours. Type 2 is the bacteriological zone in which travel times to the well are less than 60 days. Type 3 delineates the whole recharge zone of

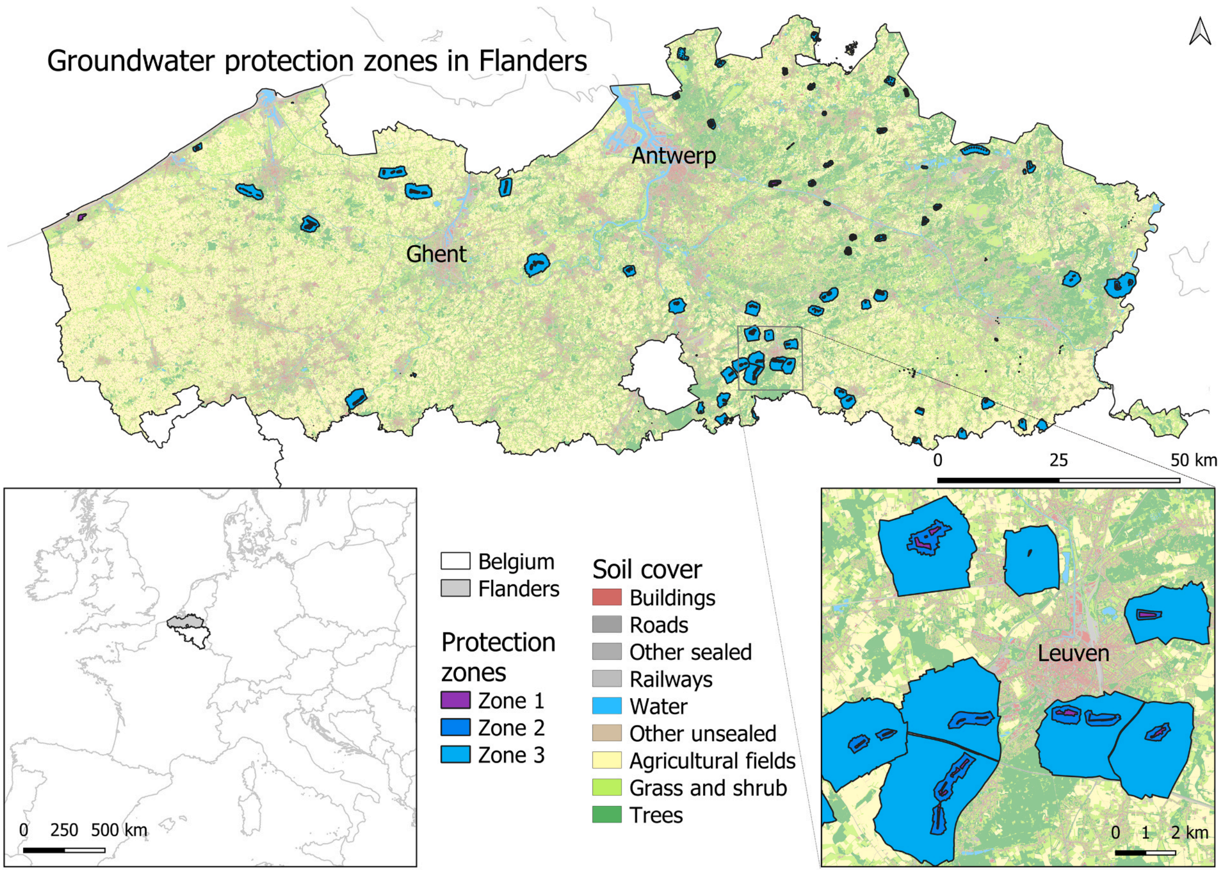

Fig. 1. Groundwater protection zones for drinking water production in Flanders (Belgium).

the groundwater well, with a maximum distance of two kilometers from the well (Databank Ondergrond Vlaanderen., n.d). These protection zones are anchored in Flemish legislation, and more stringent regulations apply to these zones, including historically an infiltration ban. However, following the increased emphasis on infiltration as a drought adaptation measure, policies are shifting. The rainwater regulation (Vlaamse Overheid, 2013) cancelled the infiltration ban for zone 3, whereas the new rainwater regulation (Vlaamse Overheid, 2023) goes further by no longer indicating any infiltration ban in protection zones.

2.2. Methodology

A quantification of stormwater infiltration potential for the enhancement of groundwater recharge was carried out by the application of a GIS-based analysis of impermeable land cover types in the protection zones around groundwater wells. Fig. 2 gives a graphical overview of the GIS analysis, whereas Table 1 provides a summary of the input data for this analysis. This analysis was carried out utilizing the open-source software QGIS (version 3.22.11) and Python (version 3.11.7).

2.2.1. GIS method to estimate available stormwater volume from impermeable surfaces for recharge

The potential yearly stormwater volumes to recharge groundwater in protection zones were calculated based on the rational method by multiplying the impervious surface area in protection zones with yearly precipitation and runoff coefficients (American Society of Civil Engineers, 1993). Additionally, correction factors for infiltration efficiency and usage of rainwater tanks are applied as not all generated stormwater will be able to recharge the groundwater system. As ranges of runoff coefficients and infiltration efficiencies vary widely in literature, worst-case and best-case scenarios with minimum and maximum values were run to account for uncertainties related to the calculated stormwater volumes. Table 2 provides an overview of used runoff coefficients and correction factors.

First, the amount of impermeable surface area for runoff generation was calculated by using a land cover map and assuming that all stormwater supplying MAR applications in protection zones stems from the protection zones themselves. This is acceptable given the fact that especially (local) infiltration measures are encouraged in Flanders, leading to water supplies coming from nearby impermeable surfaces. Furthermore, this practice is, especially since 2020, encouraged so that many infiltration projects have already been set up in non-protected areas (Integraal Waterbeleid, 2020).

The used Flemish land cover map (Agentschap Digitaal Vlaanderen, 2018) displays fourteen land cover types with a resolution of 1 by 1 m. Three land cover types were identified as urban, impermeable land cover types: 'buildings', 'roads', and 'other sealed surfaces' (e.g. parking lots). This map was overlain by Flemish drinking water protection zones (Vlaamse Overheid, 2022b) to quantify the total impermeable surface area inside groundwater protection zones by using the 'zonal histogram' QGIS tool which calculates the frequency distribution of land use types (QGIS, 2023). 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.

Next, an average yearly precipitation rate of 836 mm/year, based on data from Uccle between 1990 – 2020 (VMM, 2023), was assumed to fall on all impermeable surfaces. Minor spatial variations of precipitation rates in Flanders ranging between 740 – 950 mm/year (average in the period 1991–2020) are assumed to be irrelevant for this analysis (Koninklijk Meteorologisch Instituut van België, 2023).

The total volume of precipitation on impermeable surfaces is then multiplied by average runoff coefficients based on literature to account for losses due to evaporation, initial wetting, and seepage through cracks of sealed surfaces. Roads and other sealed surfaces (e.g. parking lots) were assigned an average runoff coefficient of 0.7 based on values established by the American Society of Civil Engineers (1993) and Angrill et al. (2017). The American Society of Civil Engineers (1993) provides ranges of runoff coefficients for various surface types, including runoff coefficients of 0.7 - 0.95 for pavements. Furthermore, Angrill et al. (2017) calculated runoff coefficients from 0.41 to 0.89 for differing road surfaces (e.g. asphalt or concrete material on roads, parking lots, or pedestrian areas).

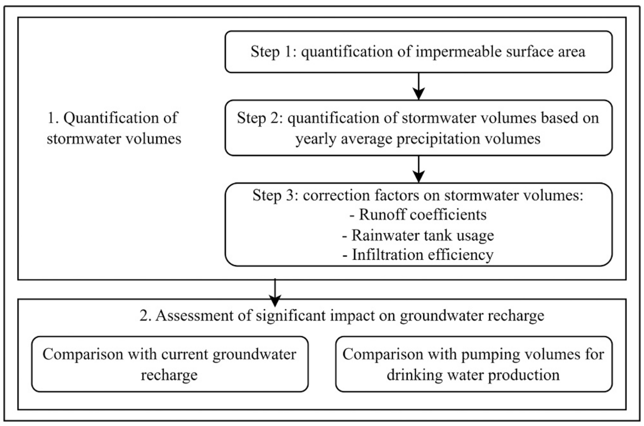

Fig. 2. Flowchart of the methodology of this research.

Table 1
Data needed for this GIS methodology.

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 ×1 m, 14 land cover types, including 3 urban land cover types (i.e. buildings, roads, other sealed) (Agentschap Digitaal Vlaanderen, 2018)
Zones of interest for stormwater harvesting and infiltration	Flemish drinking water protection zones map (Vlaamse Overheid, 2022b)
Precipitation volumes	Yearly average precipitation rate in Uccle, Brussels (1990 – 2020) (VMM, 2023)
Spatial distribution of groundwater recharge	Groundwater recharge map of Flanders based on WetSpass model outputs, 50 ×50 m (Zomlot et al., 2015)
Pumping rates for drinking water production	Maximum yearly pumping volume in the period 2016–2020 for phreatic drinking water wells of De Watergroep

Table 2
Correction factors to calculate potential stormwater volumes that can recharge the groundwater system.

Correction factor	Roofs	Roads and other sealed (e.g. parking lots)
Runoff coefficient	Min (worst-case): 0.7 Average: 0.83 Max (best-case): 0.95	Min (worst-case): 0.41 Average: 0.7 Max (best-case): 0.89
Rainwater tanks correction factor	0.9 Assumption that 10% of roof stormwater is collected in rainwater tanks	/
Infiltration efficiency	Min (worst-case): 0.4 Average: 0.63 Max (best-case): 0.98	Min (worst-case): 0.4 Average: 0.63 Max (best-case): 0.98

Similarly, an average roof runoff coefficient of 0.83 is applied based on the literature review by Farreny et al. (2011), indicating roof runoff coefficients varying between 0.7 - 0.95 for different roofing types (e.g. sloping or flat) and materials (e.g. concrete, metal, aluminium, gravel…).

Finally, the calculated stormwater volumes are multiplied by two correction factors to account for extra losses of the generated stormwater which will not recharge the groundwater system. First, the generated stormwater from roofs is multiplied by a correction factor of 0.9 to account for household rainwater tank usage. 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, 2021, 2013). Although this stimulates household water reuse for purposes such as toilet flushing and gardening, this also implies that the maximum stormwater volume for recharge will be reduced. Nonetheless, these rainwater tanks have a certain limited capacity, and the use of an infiltration facility for the overflow of rainwater tanks is strongly encouraged (Vlaamse Overheid, 2023), indicating that these two measures can be complementary as proposed in other studies (Nachson et al., 2022). The Vlaamse Overheid (2021) estimates a total rainwater usage by Flemish households and industry of 28 Mm^3/year and 22 Mm^3/year, respectively. Based on the amount of Flemish surface area indicated as 'buildings', we calculated that approximately 10% of all stormwater generated on Flemish buildings are captured in rainwater tanks.

A second average correction factor of 0.63 is multiplied by the total amount of stormwater volume to account for the infiltration efficiency of MAR facilities. However, reported infiltration efficiencies vary widely. Newcomer et al. (2014) indicate a recharge efficiency relative to incoming stormwater of 58 – 79% for low-impact developments, which is slightly higher than similar literature with 40 – 98% efficiencies. Furthermore, Bonneau et al. (2017) and Hamel et al. (2011) address the losses due to evapotranspiration (ET) in infiltration systems with vegetation in or near the facility, with Hamel et al. (2011) quantifying an ET flux of 3% of infiltration water for a raingarden in Melbourne (Australia). ET fluxes from surrounding soils (e.g., by ET from root uptake) were in this case study negligible (Hamel et al., 2011). Scholz and Kazemi Yazdi (2009) quantified higher evaporation losses, indicating a 50% loss to evaporation from rainfall falling on a car park with an infiltration facility.

2.2.2. GIS method to assess significant impacts on protection zones: comparison with current groundwater recharge and pumping volumes for drinking water production

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 for recharge were compared with the current groundwater recharge map of Flanders, simulated in the WetSpass model (50 ×50 m) by Zomlot et al. (2015). WetSpass is a water balance model that simulates groundwater recharge based on land cover, soil texture, topography, and hydrometeorological parameters. Each raster cell of a study area consists of a certain fraction of land cover types, i.e. vegetated, bare soil, open water, and impervious surface (Batelaan and De Smedt, 2007). The Flemish recharge map clearly shows higher recharge values for the Northern sand and loamy-sand areas compared to the Southern loamy soils. Additionally, lower recharge values are simulated for built-up areas, given the presence of (partially) impervious surface areas (Zomlot et al., 2015). This groundwater recharge map of Flanders was converted from mm/year to m^3/year to obtain the volume of groundwater recharge in each pixel, whereafter the total groundwater recharge in each protection zone was calculated through the sum of recharge values within the zone using the 'zonal statistics' QGIS tool (QGIS, 2023). The comparison with stormwater volumes was established by calculating the percentage of potential additional stormwater recharge compared to current groundwater recharge.

Likewise, a second comparison was made with total pumping volumes for drinking water production. Only pumping volumes from the drinking water company De Watergroep were available, thus only 25 protection zones were incorporated in the analysis. De Watergroep is however Flanders' biggest drinking water company (De Watergroep, n.d), and is responsible for 88% of the surface areas of Flemish protection zones. Only phreatic wells were included in this study, since shallow aquifers are more vulnerable to infiltration compared to confined aquifer wells, both in terms of groundwater augmentation and groundwater quality impacts (De Vries and Simmers, 2002; Machiwal et al., 2018; Simmers, 1997).

The maximum yearly pumping volume between 2016 and 2020 was taken since this was the most recent data available, 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 by calculating the percentage of potentially additional water volume compared to the pumping volumes. Therefore, this analysis assesses the ability of stormwater infiltration measures to compensate groundwater well pumping volumes.

3. Results

The results of potential stormwater volumes for recharge and their significance relative to current groundwater recharge and pumping volumes are depicted for a scenario with average runoff coefficients and infiltration efficiency. Subsequently, the uncertainty on these results is discussed by showing the worst-case and best-case scenarios for the application of stormwater MAR in Flemish protection zones.

3.1. Potential stormwater volumes from impermeable, urban surfaces

Land cover type distributions were investigated to gain an insight into imperviousness per protection zone. Fig. 3 shows the percentage of urban land cover type in the protection zones, whereas Fig. 4 depicts the distribution of different impervious land cover subcategories (i.e. buildings, roads, other sealed) within the urban land cover type. Boxplots of distribution of urban land cover fractions (Fig. 5 and 6) show a wide variability in urban land cover fraction in the different protection zones (0 – 68.58%), with an average urban land cover of 11.16%.

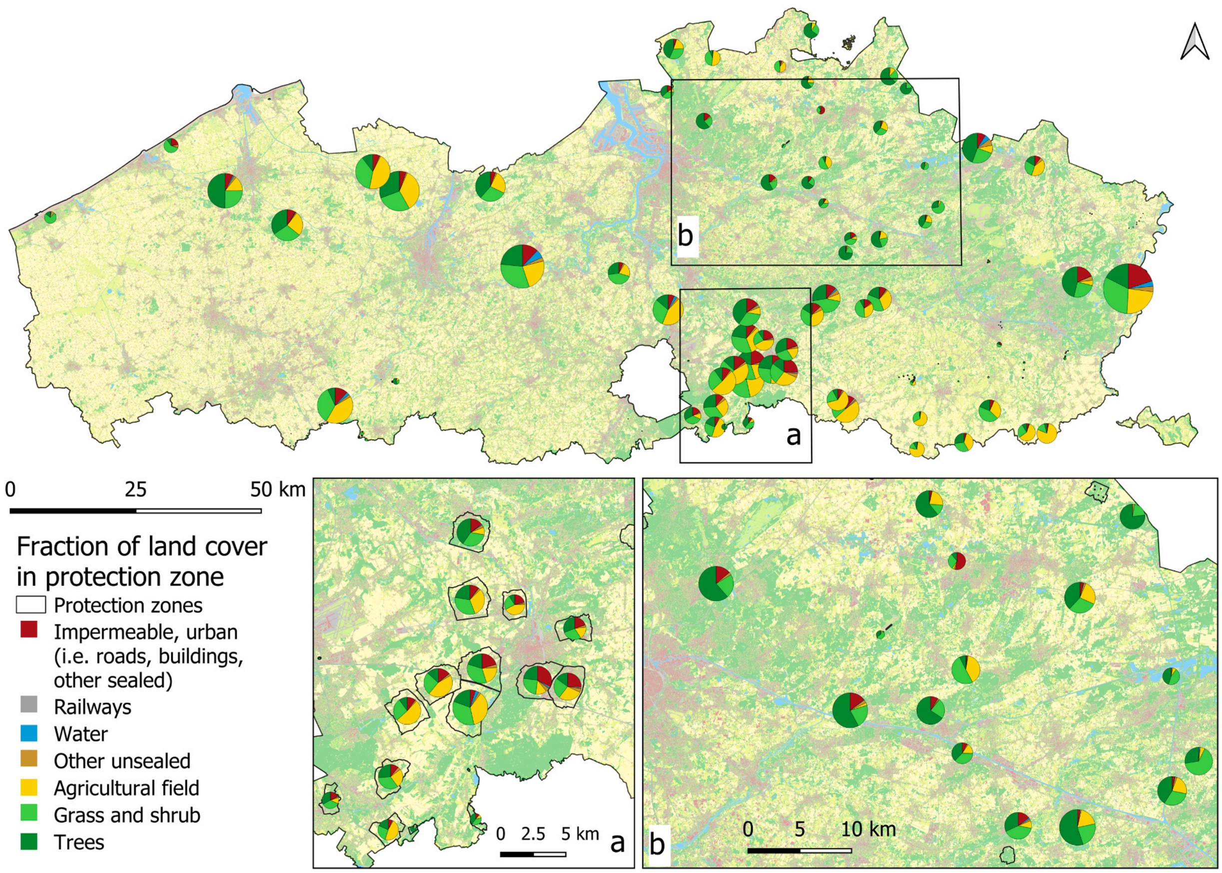

Fig. 3. Share of major land cover types in protection zones, based on Agentschap Digitaal Vlaanderen, (2018) (sizes relative to protection zone size as bigger protection zones can generate bigger stormwater volumes).

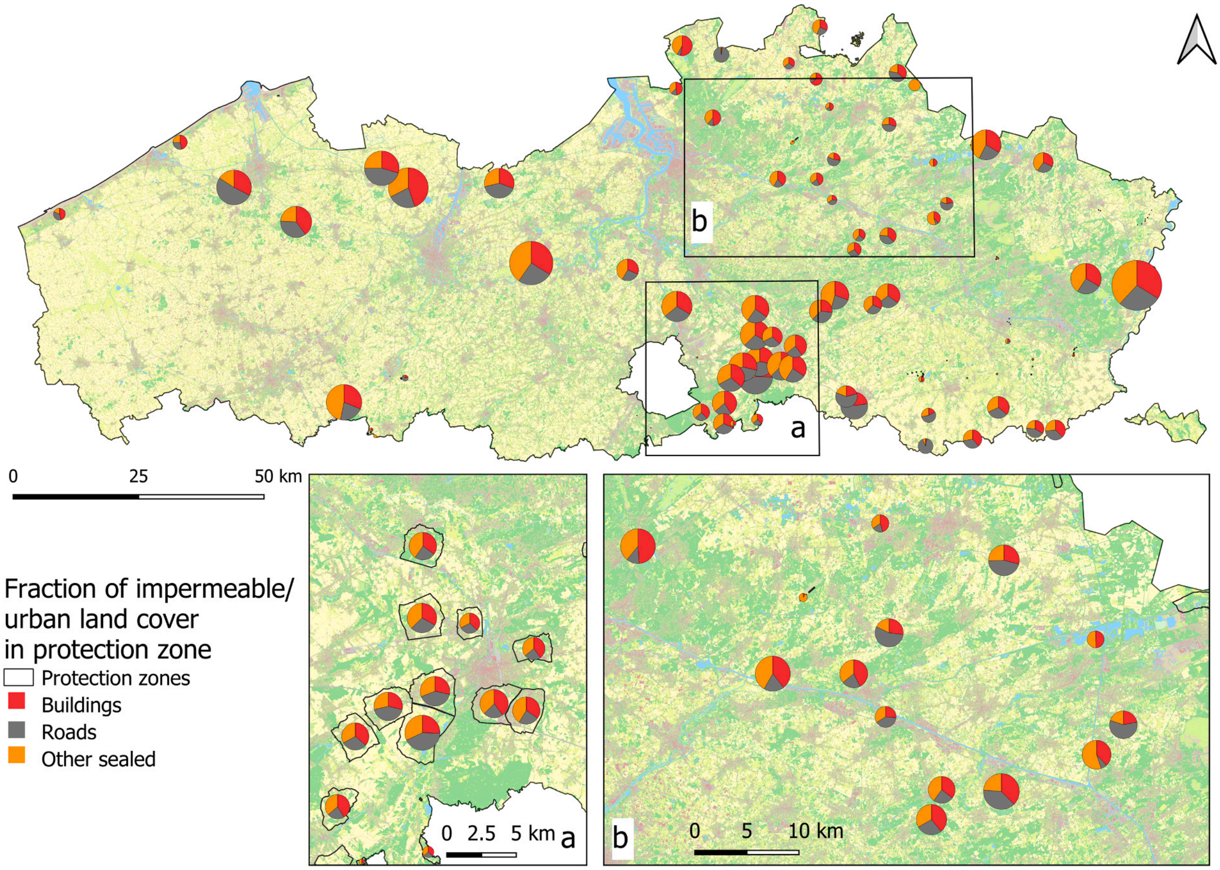

Fig. 4. Subcategories shares of urban, impervious land cover type, based on Agentschap Digitaal Vlaanderen, (2018) (sizes relative to impermeable surface area as bigger protection zones can generate bigger stormwater volumes).

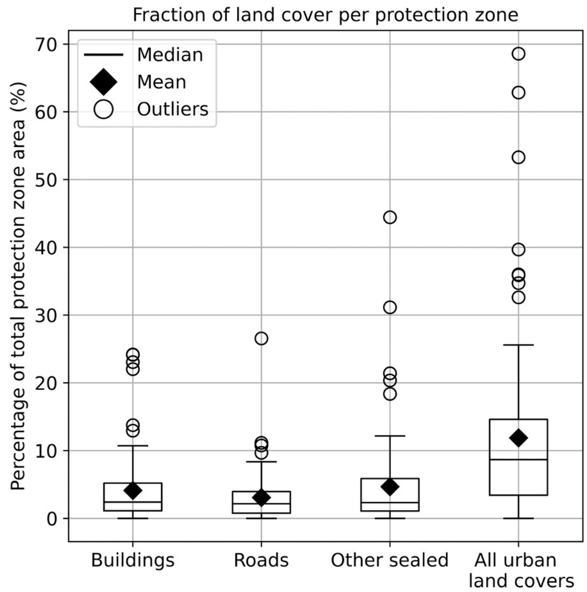

Fig. 5. Boxplots of fractions of urban land cover types within protection zones.

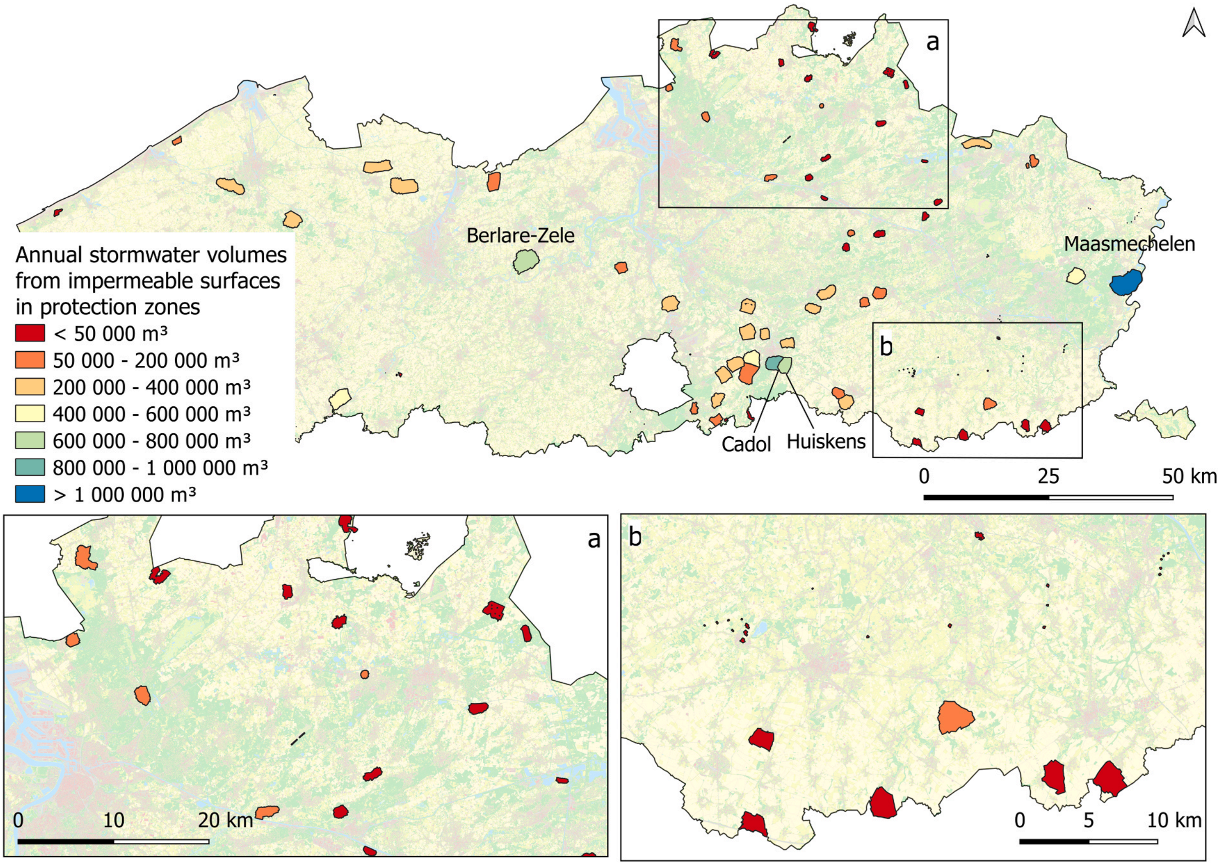

Fig. 6. Annual maximum stormwater volumes from impermeable surfaces available for recharge.

Based on this land cover map, potential rechargeable stormwater volumes from impermeable surfaces in protection zones were calculated for the average scenario (Fig. 6). Calculated stormwater volumes range between 0 and 1670830 m^3 per year, with the largest stormwater volumes in protection zones indicated with their respective zone names.

3.2. *Impact of stormwater infiltration on groundwater recharge volumes*

To put calculated stormwater volumes into perspective, a comparison is made with natural groundwater recharge and pumping rates in the protection zones to quantify the significance of stormwater infiltration for groundwater recharge volumes. Fig. 7 shows the comparison with current groundwater recharge as a fraction of yearly extra water volume from impermeable surfaces compared to the yearly groundwater recharge in protection zones. The largest protection zones with high percentages include protection zones around Leuven (Cadol, Huiskens, Herent, Egenhoven) and the protection zone in Bredene. The boxplot of percentage distributions of yearly stormwater volume versus current groundwater recharge (Fig. 9, left) shows median and average percentages of 11.92% and 22.54%, respectively. An important side note is that these values also include the very small protection zones, which are in terms of total stormwater volumes less relevant. Calculating the stormwater potential relative to current groundwater recharge in all protection zone areas combined gives a percentage of 17.13% stormwater availability compared to current groundwater recharge.

Fig. 8 compares the yearly extra water volume with yearly pumping volumes from the phreatic aquifer, similarly expressed in relative percentages. Again, higher percentages are noticeable in the area around Leuven (protection zones Huiskens, Egenhoven, Herent, Kessel-lo). Fig. 9 (right) shows the distribution of these percentages, with a median and average percentage of respectively 24.03% and 27.51%. Taking all protection zones with available phreatic pumping data combined amounts to a value of 19.21%.

3.3. *Uncertainty analysis: assessment of worst-case and best-case scenarios*

Worst-case and best-case scenarios with respectively minimum and maximum values of runoff coefficients and infiltration efficiencies were explored to account for uncertainty in the results with average correction factors. Table 3 shows ranges of stormwater volumes and average fractions of stormwater relative to current groundwater recharge and pumping volumes for the three scenarios. Figs. 10 and 11 show differences in boxplots of fractions of stormwater relative to current groundwater recharge and pumping volumes.

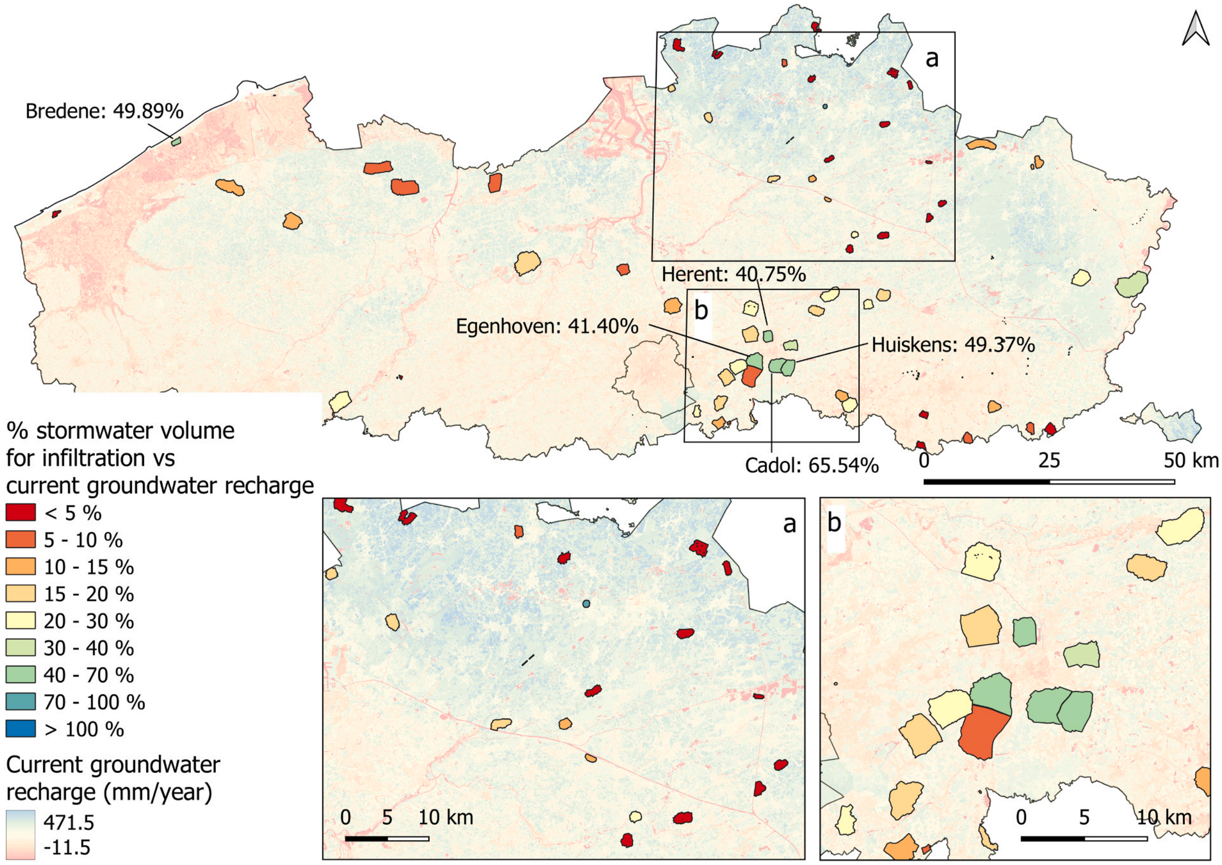

Fig. 7. Comparison of stormwater volumes for recharge versus current groundwater recharge. Protection zones with highest percentages (> 40%) and relatively big zone size (> 1 000 000 m^2) indicated with labels. Background shows current groundwater recharge.

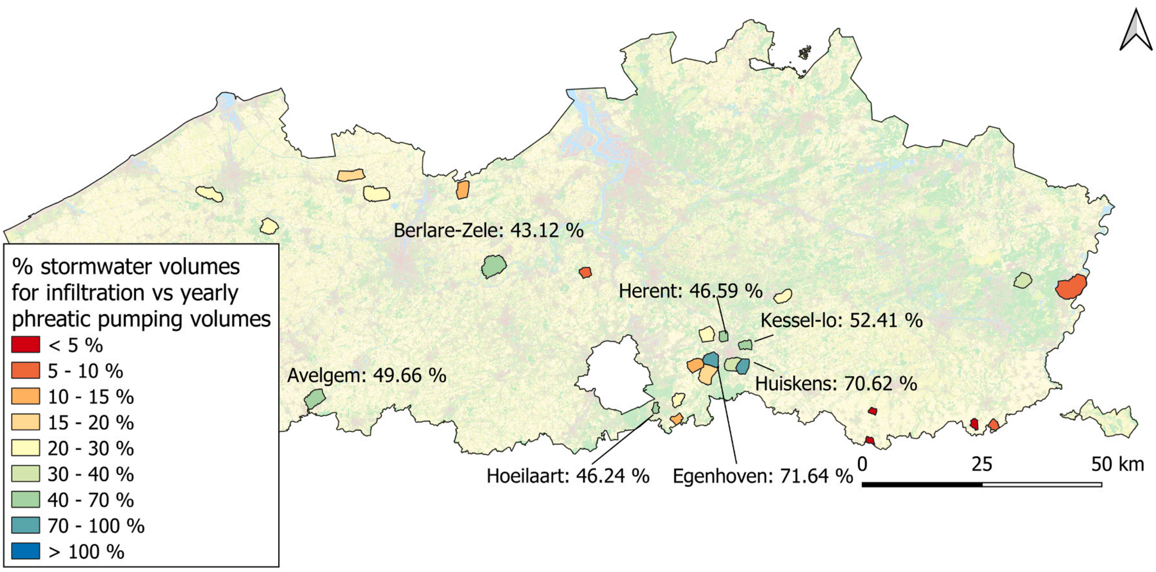

Fig. 8. Comparison of stormwater volumes for recharge versus yearly pumping volumes for drinking water production from phreatic aquifers. Protection zones with highest percentages (> 40%) indicated with labels.

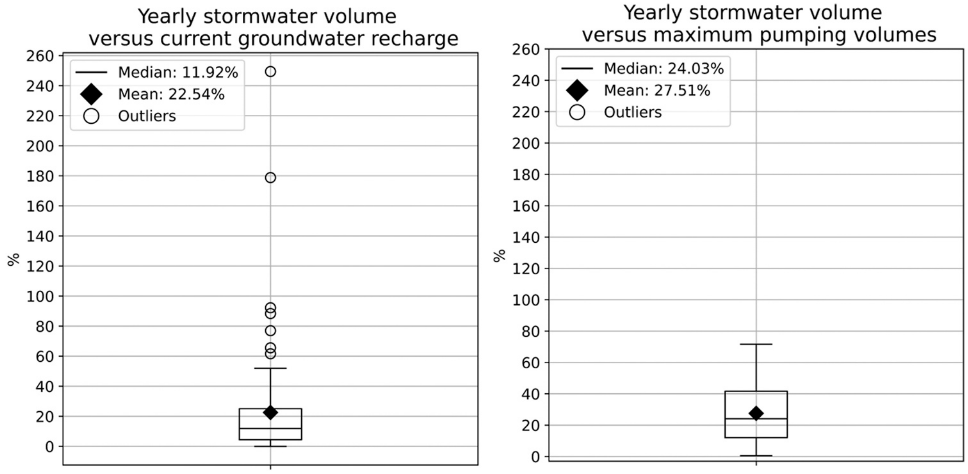

Fig. 9. Boxplots of comparison of stormwater volumes for recharge relative to natural groundwater recharge (left) and maximum pumping volumes of the last 5 years (right).

Table 3
Values of minimum and maximum stormwater volumes for recharge, and average fractions of stormwater volumes for the three scenarios.

Scenario	Minimum potential yearly stormwater volume for recharge (m^3)	Maximum potential yearly stormwater volume for recharge (m^3)	Average fraction of current groundwater recharge	Average fraction of pumping volumes
Average	0	1 670 830	17.13%	19.21%
Worst-case	0	717 910	7.37%	8.26%
Best-case	0	3 188 065	32.66%	36.64%

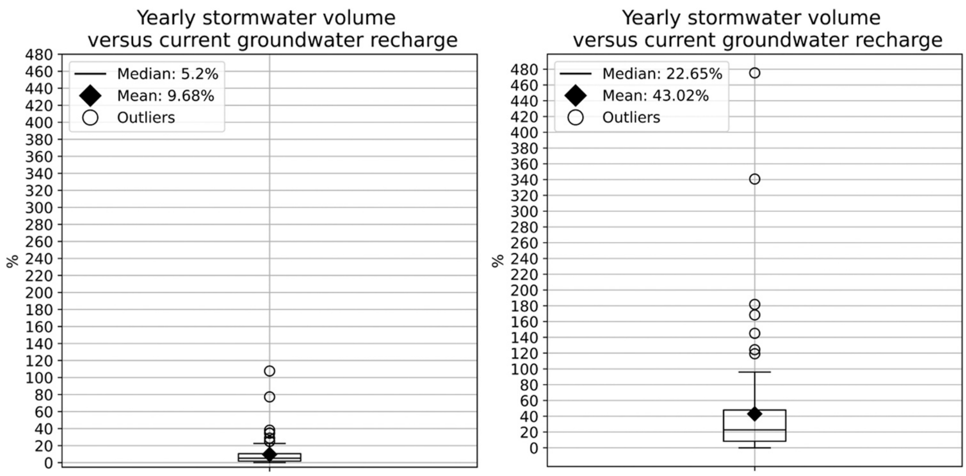

Fig. 10. Boxplots of the fraction of stormwater volume for recharge relative to current groundwater recharge for protection zones in the worst-case (left) and best-case (right) scenario for stormwater MAR.

4. Discussion

4.1. Potential stormwater volumes from impermeable, urban surfaces

The analysis of land cover types in the protection zones (Fig. 3 and Fig. 5) highlighted that a significant fraction (11.16% on average) of the protection zones consists of impermeable surfaces due to urban land cover types, which is in line with the high urbanization degree and imperviousness percentage (16%) in Flanders (De Decker, 2011; Poelmans and Van Rompaey, 2009; Statbel, 2022; Vlaamse Overheid, 2022a). However, large variations in the fraction of urban land cover types in protection zones (0–68.58%)

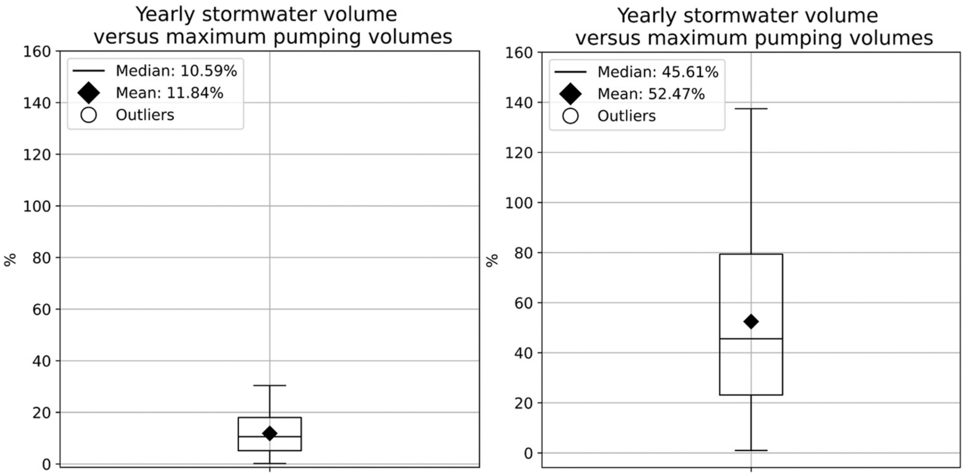

Fig. 11. Boxplots of the fraction of stormwater volume for recharge relative to annual phreatic pumping volumes for protection zones in the worst-case (left) and best-case (right) scenario for stormwater MAR.

can be related to the amount of built-up area in these zones. For example, it is specifically noticeable that protection zones in the Campine area, located in the north-east of Flanders, have smaller percentages of impermeable surfaces, given the lower population density in the area (352 inhabitants/km^2 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. Concerning the type of impermeable surface area, especially bigger protection zones show approximately equal shares of the three surface types (i.e. ‘buildings’, ‘roads’ and ‘other sealed surfaces’), resulting in approximately equal shares of the generated stormwater volumes in protection zones (Fig. 4 and Fig. 5). This is essential to consider from a water quality perspective as different impermeable surface types may contribute differently to potential stormwater pollutant composition (De Buyck et al., 2021; Gwenzi et al., 2015; Pramanik et al., 2020).

Calculated stormwater volumes for recharge (Fig. 6) generated based on the land cover analysis 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. The highest potential stormwater volume for recharge is therefore noticeable in the large protection zone of Maasmechelen. Other protection zones located south of the city of Leuven and the urban areas of Berlare and Zele show high stormwater availability because of the size and urbanization levels of these zones.

4.2. Impact of stormwater infiltration on groundwater recharge volumes

An assessment is made on how far these stormwater volumes could potentially contribute to extra groundwater recharge in Flemish protection zones through a comparison with (1) current groundwater recharge and (2) maximum pumping volumes from phreatic aquifers. The first comparison shows a high potential for extra groundwater recharge in Flemish protection zones (Fig. 7) with a wide spatial variability in potentials for different protection zones (Fig. 9, right). The highest potentials (around 40–60% extra recharge) are noticeable in protection zones around the urban area of Leuven (e.g. Huiskens, Herent, Cadol, Egenhoven). This can be explained by the urban context of the protection zones (Fig. 3), in combination with a slightly lower natural groundwater recharge given the loamy soil textures in the southern part of Flanders. Additionally, a few very small protection zones located in urban areas consist of potential extra recharge values higher than 100%, indicating a potential to double groundwater recharge, but these areas are less relevant in terms of total generated stormwater volumes and extra recharge. However, also protection zones with percentages lower than 100% have a high potential, as Fig. 7 shows that the median and average fraction of extra stormwater recharge compared to current groundwater recharge are respectively 11.92% and 22.54%. The calculated percentage for all protection zones combined amounts to an enhancement of 17.13% extra groundwater recharge by full implementation of stormwater infiltration and aquifer recharge practices in protection zones in Flanders.

A comparison with phreatic groundwater abstraction rates for drinking water production (Fig. 8) shows a similar spatial pattern, with highest potentials around Leuven (e.g. Herent, Kessel-lo, Egenhoven, Huiskens) with the ability of stormwater MAR to compensate phreatic pumping wells up to 40–70%. Also other protection zones show significant percentages, with a median and average of 24.03% and 27.51% respectively (Fig. 9, right). Taking into account protection zone sizes, the stormwater availability amounts to 1/5th of the available phreatic pumping rates in protection zones of De Watergroep.

Given the considerable uncertainty in runoff coefficients and infiltration efficiency of stormwater MAR facilities, significant differences in magnitude of stormwater potential exist when comparing the average scenario results with the worst-case and best-case scenarios (Table 3, Figs. 10 and 11). The average potential of stormwater MAR for all protection zones varies between 7% (worst-case) to 33% (best-case) extra groundwater recharge, which shows that even the most pessimistic scenario could have a considerable impact on the groundwater system. Similarly, the ability of stormwater MAR to partially compensate phreatic pumping volumes ranges between 8% (worst-case) to 37% (best-case) of the pumped volumes. Spatial patterns however remain the same for all scenarios, since the same correction factor was applied to all protection zones as data was lacking to spatially adjust these correction factors.

These comparisons show a high potential for groundwater recharge enhancement due to stormwater infiltration. Zomlot et al. (2017) calculated changes in Flemish groundwater recharge between 2006 and 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, but most likely not completely, counteract this phenomenon as calculated extra recharge values amount to approximately half of this maximum decrease. This practice can also contribute to compensating climate change impacts on groundwater recharge. Belgium is expected to experience wetter winters and dryer summers (Tabari et al., 2015), with a slight annual increase in precipitation rate of + 0.55 mm/year in Flanders (VMM Dienst Mira, 2015). This indicates that storing water between wet and dry periods, such as through infiltration facilities and MAR, is essential, and that the calculated stormwater volumes may slightly increase in future. Furthermore, 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 and remaining uncertainties, which could therefore almost completely be compensated by the predicted 17% increase in groundwater recharge from stormwater infiltration.

To conclude, this GIS analysis can complement current research on groundwater impacts of stormwater MAR systems by providing a first insight into available stormwater volumes and the significance for the groundwater system in terms of water budgets. Stormwater quantification has been predominantly applied for flood risk studies (American Society of Civil Engineers, 1993; Urban Drainage and Flood Control District, 2018), whereas the impacts of (stormwater) MAR systems are mainly assessed by modelling the effects of (local) MAR projects on groundwater recharge and groundwater levels (e.g., Bhaskar et al., 2018; Endreny and Collins, 2009; Ringleb et al., 2016). However, this GIS analysis can analyse the potential of infiltration and MAR systems supplied by stormwater on a higher, regional, or national level. This map can be used by stakeholders in the water sector such as drinking water companies, in the initial phase of stormwater infiltration and MAR implementation by prioritizing locations with high potential in terms of stormwater supply. Further steps into implementing these practices need to take into account the suitability (e.g. geology, soil type…) for MAR applications (Rahman et al., 2012; Sallwey et al., 2019) and water quality aspects as the stormwater may contain pollutants (Angrill et al., 2017; Fairbairn et al., 2018; Sánchez et al., 2015).

4.3. Limitations of the proposed methodology

A few assumptions were made in order to carry out the GIS analysis performed in this study. Average runoff coefficients for stormwater from roofs and roads were based on literature (American Society of Civil Engineers, 1993; Angrill et al., 2017; Farreny et al., 2011). It was not possible to further distinguish this runoff coefficient as no data was available on the different roofing and road materials on the used land cover map (e.g. concrete or asphalted roads, and clay tiled or metal roofs). However, uncertainties regarding this value were taken into account by providing worst-case and best-case scenarios with minimum and maximum runoff coefficients. Furthermore, all urban surfaces (i.e. roads, roofs, 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, as the conversion of impermeable to (semi-)impermeable surfaces is encouraged in Flemish regulations (Integraal Waterbeleid, 2020).

Furthermore, the choice was made to compare yearly volumes of stormwater and groundwater recharge, consequently missing potentially important time-dependent processes. Rainfall events vary in intensity, frequency, and duration, causing differences in runoff coefficient and amount of generated stormwater per rainfall event (Beganskas and Fisher, 2017; Nachson et al., 2022). Furthermore, infiltration facilities have a certain maximum capacity, which can lead to overflow of excess precipitation during peak rainfall events (Bhaskar et al., 2018). However, given the time scale of input data for this study, the decision was made to focus on yearly averaged values.

A last important 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 asses flow paths and residence times of the infiltrated water, future research is needed that assesses the impacts of infiltration measures on groundwater levels and groundwater fluxes, using groundwater modelling as a tool to incorporate principles of groundwater flow (Ringleb et al., 2016).

5. Conclusion

This paper presents a novel approach to assess the spatial variability of stormwater availability for infiltration and MAR practices, and to investigate its significance for the enhancement of groundwater recharge. This methodology was applied to drinking water protection zones in Flanders, where the ban on infiltration was recently cancelled to deal with drought and flooding in the region, making it essential to develop decision tools to weigh out water quantity-quality aspects of stormwater infiltration practices. Therefore, this research aimed to assess if available stormwater volumes can significantly contribute to groundwater recharge in these protection zones.

Results indicate a high, although spatially variable, 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 a high stormwater recharge potential from impermeable surfaces (i.e. roofs, roads, parking lots). In these areas, groundwater recharge can potentially be enhanced by approximately 40–60% if all stormwater would be used for infiltration and aquifer recharge. Furthermore, yearly pumping volumes can be compensated up to 40–70% by these stormwater volumes. Other protection zones show lower, but significant stormwater volumes for additional groundwater recharge with an average potential of 17% (7% worst-case, 33% best-case) additional groundwater recharge and a potential compensation for 19% (8% worst-case, 37% best-case) of abstracted groundwater for drinking water production from phreatic aquifers. This shows that it is important to further encourage infiltration and MAR practices throughout the whole region, given the high urbanization level of Flanders (De Decker, 2011; Statbel, 2022). Special attention must be given to urban areas such as protection zones around the city of Leuven, as this analysis shows a high stormwater MAR potential for these areas. Additionally, natural groundwater recharge has declined in urban areas due to urban expansion and associated increases in imperviousness (Zomlot et al., 2017).

As stormwater supply mainly stems from urbanized areas in Flanders, this shows that it would be especially beneficial to apply the proposed GIS methodology in other urban areas to gain a first insight into the stormwater supply potential. This method can serve as a screening tool to quickly assess the spatial hotspots of stormwater availability for infiltration and MAR applications. The methodology can be applied to other spatial data on land cover in a study area. However, a detailed, high-resolution land cover map with a clear indication of impermeable surfaces will provide the most accurate estimation of the amount of impermeable surfaces and associated stormwater volumes. This GIS method can then be used for prioritizing stormwater infiltration projects in areas with high potential stormwater supply.

Further 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, future 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 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, 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.

CRediT authorship contribution statement

Marijke Huysmans: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Jef Dams:** Writing – review & editing. **Goedele Verreydt:** Writing – review & editing. **Dirk Gijsbert Cirkel:** Writing – review & editing, Supervision, Funding acquisition. **Bas van der Grift:** Writing – review & editing, Supervision, Funding acquisition. **Simon Six:** Supervision, Conceptualization. **Lara Speijer:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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