Report Crossborder precipitation monitoring network.

*The EMfloodResilience project is being carried out within the context of Interreg V-A Euregio MeuseRhine and is 90% funded from the European Regional Development Fund.*

## Contents

# 1- A description of the principles for a well-designed area-covering precipitation monitoring network

AMO-meteo is conducting a study on behalf of the Limburg Water Board (WL) to optimize a precipitation monitoring network that complies with the guidelines and recommendations for rainfall measurement according to KNMI and WMO. The objective is to establish an optimal network in terms of density and geographical distribution of high-quality, representative rainfall stations within the WL management area and its drainage and watershed areas.

Based on the recently published climate scenarios '23 by KNMI, it is projected that in a warmer climate, there will be more winter rainfall and more frequent extreme summer showers. Winters will become wetter, while summers will become drier overall. However, when it does rain in the summer, it will rain more intensely. These intense showers, characterized by high intensity and duration, necessitate effective monitoring. A denser network of rainfall stations will significantly enhance the quality of monitoring. The rainfall stations report in real-time based on five-minute data. The number of monitoring stations is crucial for tasks such as correcting radar products. Both radar rainfall data and ground station data are essential for a reliable final product. The more local stations included, the better local deviations in radar products can be corrected. Urban stations are less suitable for this purpose due to their limited representativeness for larger areas. Rainfall stations in the 15 km wide border area of WL are vital for the stability and quality of correction algorithms. The use of these data points depends on the representativeness of the respective locations and the type of rain gauge in use.

*KNMI: Koninklijk Nederlands Meteorologisch Instituut - WMO: Wereld Meteorologische Organisatie – ISO; International Organization for Standardization*

## 1.1 Precipitation Monitoring Density

The amount and intensity of precipitation can vary significantly at the local level. This is especially true under unstable atmospheric conditions, such as during the passage of narrow disturbances or local thunderstorms (heat thunderstorms). Therefore, a relatively high monitoring density is required for hydrology and climatology precipitation networks. In relatively homogeneous landscapes, this density should be approximately 1 precipitation station per 100 km². However, in or near urban areas, rugged terrains, hilly regions, transitional zones (e.g., land-water interfaces), or river areas, a higher monitoring density is desired, roughly around 1 station per 70 km². This increased density is crucial for accurately capturing the diverse precipitation patterns, especially in regions prone to rapid weather changes and localized heavy rainfall events.

## 1.2 Orographic effects

In the case of strongly rugged terrain, such as hills, dunes, and mountains, forced uplift of air can occur, accompanied by a drop in temperature and possible cloud formation if the condensation level is exceeded. Precipitation can occur on the windward side as a result. Due to the relatively low elevation of "mountains" in our country, these so-called orographic effects are expected to be limited. However, the hills in the province of Limburg, especially those in the hilly region of South Limburg, on the Veluwe, and in the provinces of Overijssel, Drenthe, and Utrecht, may lead to additional precipitation of approximately 1 mm per day.

## 1.3 Influence of Water-Land Transitions on Precipitation Distribution

When humid air flows over relatively cold water surfaces towards land with a comparatively warm surface, the lower layers of the air are quickly heated, leading to instability. In autumn or winter, polar cold air can sweep over relatively warm water surfaces, becoming highly unstable as a result. This situation leads to strong convection and the formation of cumulonimbus clouds. Showers that occur both in summer and in winter/fall develop and move inland at water-land transitions, causing the atmosphere above the land to quickly stabilize again. Along the coastal zone, extra precipitation amounts and more intense rainfall can be recorded compared to inland areas. Differences of several millimeters in precipitation within relatively short distances are not uncommon. Major rivers (such as the Maas) can influence the distribution of precipitation, especially during thunderstorms, particularly when there is heat lightning.

## 1.4 Urban Effects on Precipitation

In an urban environment, the climate, including precipitation patterns, differs from the flat surroundings outside the city. Deviations in precipitation can be explained by various factors such as thermal effects due to higher temperatures, atmospheric instability caused by greater surface roughness, increased humidity resulting from industrial activities, and reduced moisture absorption compared to vegetated landscapes. Particularly during heavy rainfall, differences in precipitation amounts within an urban area compared to the surrounding region can be substantial. Although this phenomenon is still the subject of ongoing research, estimates suggest that in a large city, during average regional precipitation events exceeding 25 mm, there can be 30 – 90% more rainfall.

## 1.5 Radar Product

The Royal Netherlands Meteorological Institute (KNMI) utilizes a radar product generated by accumulating successive reflectivity images from its precipitation radars. This process creates a precipitation image with high spatial and temporal resolution. However, it is known that several factors complicate the quantitative interpretation of radar precipitation data. The main factors, illustrated in *Figure 1*, include the height of the radar beam above the Earth's surface, variations in the droplet size spectrum, and attenuation during intense rainfall. Additionally, a flock of birds/insects or an airplane can cause 'false alarms,' also known as noise or clutter. Current observations from a precipitation monitoring network (ground stations) are fundamentally suitable for correcting these errors in radar products. This approach combines the best of both worlds: the (high) resolution of radars and the (local) accuracy of the monitoring stations.
Disdrometers are not suitable for this purpose because they do not directly measure precipitation quantity but are derived from measured parameters such as droplet size and terminal velocity (size distribution). However, disdrometers are ideal for validating radar reflectivity measurements.

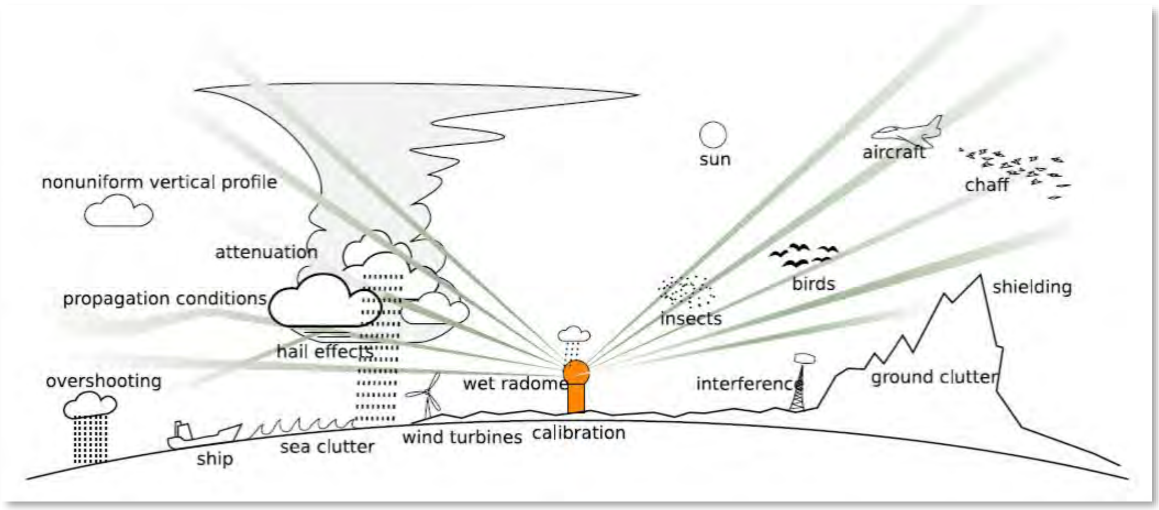


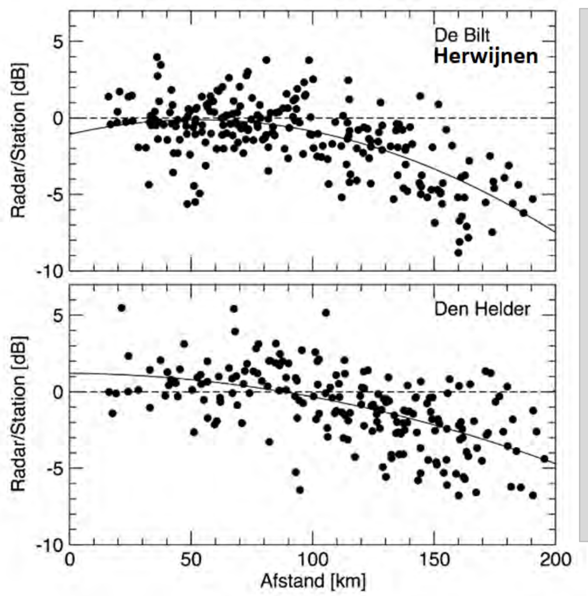

*Figure 1*

The most significant challenge in correcting radar products lies in the disparity in representativeness between radar observations and measurements from ground stations. A precipitation radar captures large volumes at a considerable height (several km³), approximately 1.5 km above the Earth's surface, whereas precipitation observations from ground stations are only indicative of a small area surrounding the measurement location. Furthermore, the size of this area depends on the type of precipitation: stratiform (large-scale rainfall) or convective (small-scale showers). This especially complicates the extrapolation of ground station measurements to the volume for which radar observations are representative, particularly during convective rainfall. This representativeness gap results in typical deviations of approximately 50-100% in precipitation (daily) totals.
When correcting radar products using the precipitation monitoring network, these representativeness differences must be consistently taken into account. Failure to do so would introduce errors into the correction procedure rather than reducing them. Depending on a specific precipitation monitoring network, limitations exist regarding the spatial and temporal resolution at which the correction can be applied.

## 1.6 Differences in Representativeness

An impression of the magnitude of differences in representativeness between radar grid points and station observations can be obtained from *Figure 2*. This figure provides a comparison of 24-hour precipitation accumulations from two radars, De Bilt (until early 2017) and Herwijnen (from late 2016), with those from 325 manual measuring stations (08:00 – 08:00 UTC) of the KNMI concerning the distance to the radar. The full spread of the data points around the curve is approximately 3 dB (a factor of 2, +/- 50%), determined by the differences in representativeness and the (limited) local variations. Comparison of daily totals between pairs of neighboring precipitation measuring stations yields a standard deviation of 1.14 mm on an average daily total of 2.43 mm.

Here too, the spread is approximately +/- 50%. A commonly applied rule of thumb is that the full representativeness error is approximately a factor of 2 for the comparison of a daily total from a radar grid point and a measuring station. By averaging a (large) number of combinations of radar grid points and station observations, the statistical error due to representativeness differences can be reduced, effectively correcting the systematic errors in radar data.
Therefore, it is essential to take these differences into account when correcting radar products; otherwise, discrepancies of 100% or more could be introduced.




← *Figure 2*
Comparison 24-hour precipitation from radar stations (De Bilt and Den Helder) and 325 hand precipitation stations for a day as a function of the distance to the radar.

The significant differences in dB between the radars (De Bilt/Herwijnen and Den Helder) are attributed to representativity variances and limited local variations. *Figure 2* provides visual insight into this comparison, illustrating substantial variations in precipitation measurements between the radars and those from the manual measurement stations, particularly based on the distance from the radar.

## 1.7 Representativeness Error

To minimize the representativeness error in correcting radar images, a sufficient number of pairs of radar grid points and ground stations that have effectively recorded a certain amount of precipitation must be available during a rainfall event. For large-scale precipitation and long accumulation periods, after the establishment of WL's recommended monitoring network, acquiring enough pairs of radar stations with observed precipitation within the management area will not be an issue.

WL's management area covers an area of 2210 km$^2$. Based on the proposed density situations for WL with eighteen (18) precipitation stations, according to the rule of thumb, the representativeness error on a daily basis will be a maximum of 11.6% (50% / √N). With the addition of three KNMI stations, the representativeness error on a daily basis will be a maximum of 10.6%.
For large-scale precipitation, accuracy will be higher due to the influence of the national monitoring stations. However, during showery weather with small-scale structures and short time scales, extra caution must be exercised. In such situations, if there are insufficient pairs of radar stations with observed precipitation available, the correction error can significantly increase, making it often better not to correct using real-time data.
Given the above, it is not advisable to correct radar products on time scales shorter than one hour: for large-scale (stratiform) precipitation areas, it is unnecessary, and for small-scale (convective) precipitation systems, there is a risk of significant errors.
*Table 1* provides an estimation of the size of the representativeness error on a daily basis as a function of the number of monitoring stations, the main error source in correcting radar products with ground stations.
The number of stations refers to those actually involved in the correction of the radar product, depending on the weather situation, accumulation period, and the algorithm used.

The first row in *Table 1* represents the situation if there is (in theory) one operational precipitation station in the WL management area. The second row represents the situation with the current number of WL's precipitation stations, in parentheses if the three KNMI stations are involved in the correction. The third row represents the number of WL's precipitation stations, including eight (8) recommended stations, in parentheses including the three KNMI stations. The fourth row is applicable to the national KNMI network of 35 automatic precipitation stations. The representativeness error is smaller, but the coverage area is larger. To achieve a comparable accuracy on a smaller area with more detailed information ('higher resolution'), a higher monitoring density is required.

*Note that the KNMI network of 35 automatic precipitation stations (00:00 - 00:00 UT) has a density of approximately one station per 1000 km². The manual precipitation monitoring network (08:00 – 08:00 UT) of the KNMI has a density of approximately 1 station per 110 km².*

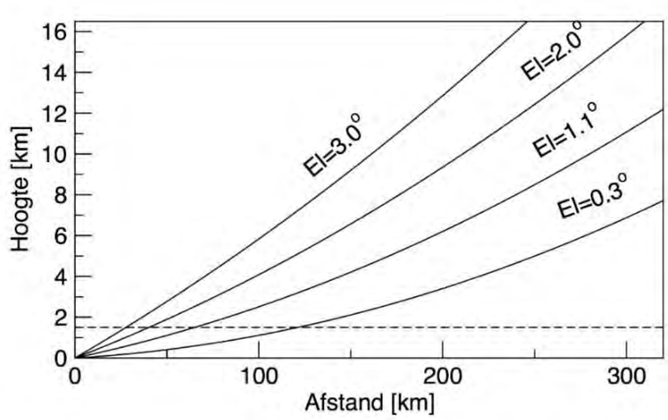
| *Density of ground stations* | *Number of stations in the management area* | *Representativeness error* |
|---|---|---|
| 1 per 2210 $km^2$ | 1 | 50% |
| 1 per 201 $km^2$ (158 $km^2$) | 11 (14) | 15% (13,5%) |
| 1 per 116 $km^2$ (100 $km^2$) | 19 (22) | 11,6% (10,6%) |
| 1 per 1000 $km^2$ | 35 | 8% |

*Table 1*

## 1.8 Geometry of the KNMI Radar Network

The quality and representativeness of radar observations strongly depend on the distance from the radar antenna. Due to the curvature of the Earth and the elevation angle (El, angle with the Earth's surface) of the radar antenna, the height of the radar beam increases with distance.

In *Figure 3*, the height above the Earth's surface is plotted as a function of distance for elevations typically used by KNMI's operational precipitation radars. The dashed line marks the height of the standard radar image. The lowest elevation (0.3 degrees) reaches a height of almost 3.5 km at a distance of 200 km! At this height, observed precipitation intensities can significantly differ from those at the ground, and in winter situations, it is possible that drizzle and light snow are not detected. Furthermore, the radar's measuring volume also increases with distance, leading to larger differences in representativeness between radar grid points and precipitation stations.




← Figure 3

*The height (left) of the radar beam above the earth's surface as a function of the distance (under) to the radar for elevations typically used by operational precipitation radars. The striped line marks the height of the standard radar image (1.5 km).*

## 1.9 Precipitation Radars in Herwijnen and Den Helder

KNMI's operational radar products are based on data from two relatively new Dutch radars of the *'dual-polarization'* type, located in Herwijnen and Den Helder. Using a composite method based on a distance-weighted average, the measurement data from both radars are combined into one national precipitation product.

At very short distances (<10 km), the quantitative use of radar observations remains a scientific and technical challenge, but at distances between 10 and 100 km, the observations have the highest quality. This is due to the low measurement height, short distance, and relatively small measuring volume.
Considering the location of Roermond, roughly the center of WL's management area, the KNMI precipitation radars in Den Helder and Herwijnen are located at approximately 214 km and 92 km, respectively. When used quantitatively, it is important to monitor whether both radars contribute to the radar product because the failure of a precipitation radar can significantly impact the accuracy of precipitation products.

## 2- A Description of the Installation Requirements for a Precipitation Rain Gauge

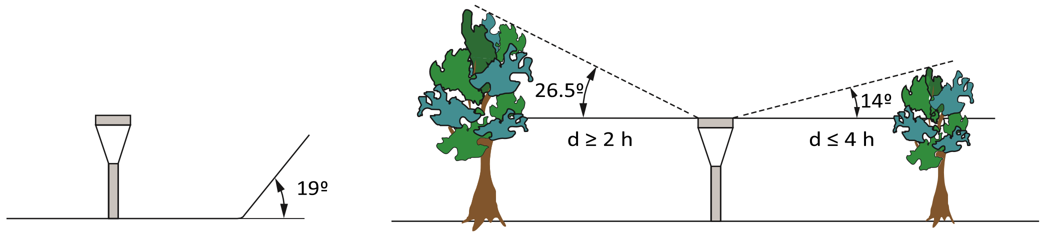
The precipitation gauge setup must allow rainfall to freely enter the collecting funnel or sensor surface from all directions. The immediate vicinity around the sensor should be horizontal and may be covered with grass, short ground cover, soil, or gravel. Hard, flat surfaces are undesirable due to the risk of splashing water, which could enter the instrument.
Some distant shielding is desired to prevent rain or snow from being blown by the wind. The precipitation gauge should be placed and maintained horizontally. The standard measuring height is 40 cm, or 1 meter above the ground. At the latter installation height, a wind reduction screen must be placed around the precipitation gauge.
Wind represents the primary source of interference in precipitation measurements due to its impact on the instrument's airflow. Unless rain gauges are protected against wind, for example, by a wind shield, the most suitable sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or in areas where other objects act as effective windbreaks from all directions. Ideally, the installation should occur in an area uniformly surrounded by obstacles of uniform height. An obstacle is defined as an object with an effective angular width of 10° or more. Selecting such a site might not always align with height constraints of other measuring equipment, making these conditions practically unrealistic.

If obstacles are not uniform, they can create turbulence, distorting measurements, especially for solid precipitation. Therefore, more realistic elevation guidelines specify a certain distance from any obstacles. The orientation of these obstacles concerning the prevailing wind direction is deliberately not considered. Heavy precipitation often involves convective factors, where wind direction might not align with the prevailing wind. Obstacles are considered to have a uniform height if the ratio between the highest and lowest height is less than 2.

### 2.1 Reference for the heights of obstacles is the catchment's height of the raingauge

Class 1

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). The raingauge shall be surrounded by low obstacles of uniform height, that is subtending elevation angles between 14° and 26° (obstacles at a distance between 2 and 4 times their height);
(b) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). For a raingauge artificially protected against wind, the instrument does not necessarily need to be protected by obstacles of uniform height. In this case, any other obstacles must be situated at a distance of at least 4 times their height.

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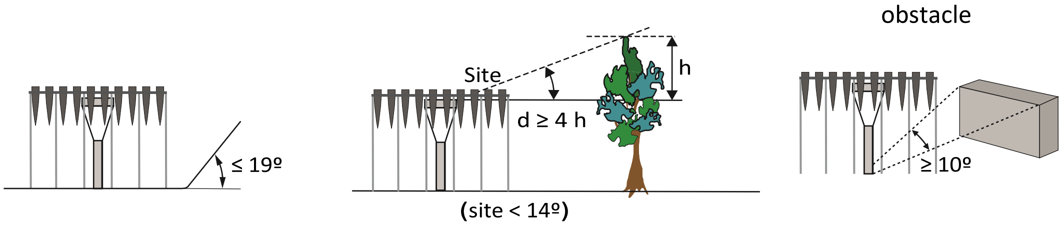



*Figure 4 Criteria for precipitation for class 1 sites*

Class 2 (additional estimated uncertainty added by siting up to 5%)

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°);

(b) Possible obstacles must be situated at a distance at least twice the height of the obstacle (with respect to the catchment's height of the raingauge).

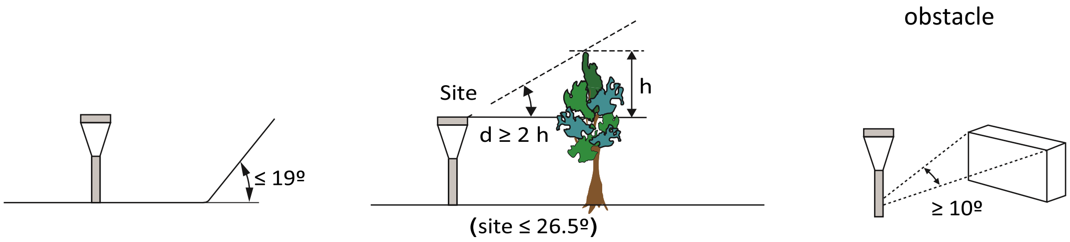



*Figure 5 Criteria for precipitation for class 2 sites*

Class 3 (additional estimated uncertainty added by siting up to 15%)

(a) Land is surrounded by an open area, slope less than ½ (≤ 30°);

(b) Possible obstacles must be situated at a distance greater than the height of the obstacle.

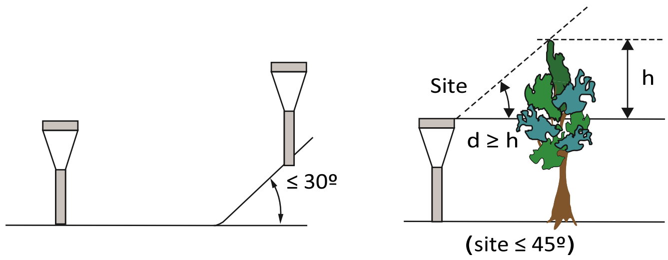



*Figure 6 Criteria for precipitation for class 3 sites*

Class 4 (additional estimated uncertainty added by siting up to 25%)

(a) Steeply sloping land (> 30°);

(b) Possible obstacles must be situated at a distance greater than one half (½) the height of the obstacle.

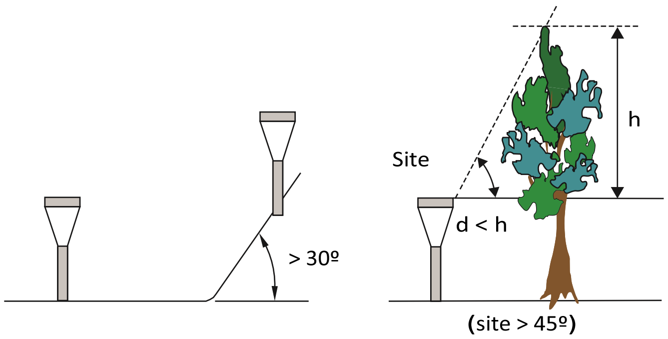



*Figure 7 Criteria for precipitation for class 4 sites*

Class 5 (additional estimated uncertainty added by siting up to 100%)
Obstacles situated closer than one half (½) their height (tree, roof, wall, etc.).

*Figure 8 Criteria for precipitation for class 5 sites*

| WMO Class | Reference | Relative obstacle distance[1] | Obstakels: |
|---|---|---|---|
| 1 | Recommendations | > 3,5 - 5 | at more than sufficient distance or irrelevant |
| 2 | Good | > 2 - 3,5 | at a sufficient distance |
| 3 | sufficient under conditions [2] | > 1 - 2 | at a minimum distance |
| 4 | insufficient | 1 | within the minimum distance |
| 5 | not usable | < 1 | well within the minimum distance |

*Table 2*

[1] *relative obstacle distance = obstacle distance divided by obstacle height*

[2] *if it is possible to achieve a higher WMO class at the location, for example by pruning or felling trees*

## 2.2 Quality Assurance

In addition to being located in a representative area, a precipitation station must continue to meet the criteria outlined above (recommendations and guidelines of the WMO). In other words, the quality and representativeness of the measurement location and the sensor in use must be guaranteed at all times.
A spatial inspection of the precipitation station occurs biennially (once every 24 months). The environmental conditions are compared to those of the last inspection.
Maintenance and calibration of the balance sensor are performed annually. This calibration is essential when using a precipitation gauge based on the weighing principle, as is the case with WL.

### 2.3 Spatial Inspection

During a spatial inspection, the surrounding environment is assessed within a 0-360 degree range according to national and international standards established by KNMI and WMO. Using laser measurements, relevant obstacles are surveyed and compared with the results of the most recent spatial inspection or survey.
Attention is paid to the roughness of the environment, as well as the distance, height, and angular space of obstacles that could potentially impact precipitation measurements.
The evaluation determines whether the quality and representativeness of the measurement in all directions within the 0-360 degree range are adequate. Changes in spatial conditions might affect the WMO classification assigned to a specific location.
The inspection report indicates whether there are action points, areas for improvement, or specific areas requiring attention.

### 2.4 Maintenance and Calibration of Precipitation Gauge, Based on the Weighting Type Used at WL

The accuracy test of the balance sensor is conducted on-site and includes:
-Calibration of the balance sensor;
-Firmware update (if necessary);
-Calibration report (including certificate).
Additionally, a physical inspection of the precipitation gauge for visible defects is carried out. The collection reservoir and the instrument casing are also cleaned. To prevent damage to the plastic collection container during moderate to severe frost, adding 1 to 1.5 liters of antifreeze to the reservoir provides adequate protection.
These tasks are preferably performed in the month of October, at the beginning of the winter season.

## 3- A description of an optimal precipitation monitoring network for Limburg and the border region

The management area of WL borders two Dutch neighboring water boards, namely Aa en Maas and De Dommel. Within the WL management area, there are also three (3) automatic recording rain gauges operated by the KNMI, also known as 'AWS stations,' where precipitation is measured automatically (0 - 24 UTC).
WL shares borders with several foreign organizations that also conduct precipitation measurements. These organizations include DWD/Hygon, KMI, WVER, Niersverband, VMM, and SPW.

### 3.1 Relevant Landscapes

Within the WL management area, relevant landscapes and/or areas have been identified that can have a specific impact on the precipitation climate and/or the distribution of rainfall. These areas are crucial input for station selection within or near such regions. The relevant landscapes and/or areas are:

- *Urban area*
  Venray
  Venlo
  Roermond
  As Born-Buchten-Susteren
  As Sittard-Geleen-Stein-Elsloo-Beek
  Kerkrade
  Maastricht
  As Horst-Sevenum
  As Nederweert-Weert
  As Brunssum-Heerlen-Landgraaf-Kerkrade

- *Nature reserve*
  Boschhuijzer Mountains, Houthuizerheide, Weerterbosch, Meinweg National Park .

- River, Canal, and Lake Area
  Maas Valley, Geul Valley, Julianakanaal, and the lake area near Roermond.

- *Hilly area*
  The southern management area of WL, south of the town of Sittard - approximately from the coordinate line Y: 330.00.

## 3.2 Optimal Measurement Density and Geographic Distribution in the WL Management Area

An optimal precipitation monitoring network consists of a representative distribution and geographic density of precipitation stations. This representation aligns with the type of landscape and area where precipitation measurements occur.

Currently, the operational precipitation monitoring network of WL comprises eleven (11) stations. The density is unevenly distributed in relation to geographical locations. It is denser in the southern part compared to the northern part of the province.

These stations use a type of precipitation gauge based on the weighing principle. Within the management area, there are three AWS stations operated by KNMI: Arcen, Ell, and Maastricht AP. WL shares borders with the neighboring water boards De Dommel and Aa en Maas. Precipitation stations from these water boards are situated within the 15 km wide border area of WL. In this border area, the KNMI AWS station Volkel is also located.

For the research within the WL management area, a GIS map was created, displaying grid cells of 10 x 10 km² based on Amersfoort coordinates. On this map, the eleven precipitation stations of WL, the AWS stations of KNMI, and those of the water boards De Dommel and Aa en Maas were plotted. The stations of the neighboring water board Aa en Maas fall into WMO classes 1 and 2.

The measurement instrument used is of the weighing type (brand: OTT pluvio²). Water board De Dommel uses precipitation gauges of the Tipping Bucket type (brand: Observator). The WMO class for these stations is not available. The KNMI locations, of course, adhere to the guidelines for precipitation measurements, ensuring their quality.

After analysis, relevant areas within the WL management area were identified. In eight (8) of these areas, a recommended precipitation station was plotted, indicated by a black triangle in *Figure 9*. This map represents the optimal situation for the density and geographic distribution of precipitation stations in the WL management area. For a recommended station within a specific 10 x 10 km² grid cell, a search circle with a radius of 5 km is used. A recommended station preferably resides on a WL location or other government-owned land.

The WL management area covers an area of **2210 km².** Based on the current number of stations, the density is 1 station per **201 km²**. Considering the recommended monitoring network, the density becomes 1 station per **116 km².**

Note: For both density scenarios, KNMI AWS stations within the WL management area are excluded.

→

In the red circles a recommended measuring point (1 to 8), indicated by a black triangle.
Explanation (in parentheses the number of drives):
Blue sphere: KNMI - AWS (4)
Yellow sphere: Precipitation gauge WL (11)
Green sphere: Water board Aa en Maas (4)
Red sphere: De Dommel Water Board (1)

| | Advised precipitation station |
|---|---|
| 1 | *east of the town of Ysselstein* |
| 2 | *east of the town of Horst* |
| 3 | *north of the town of Weert* |
| 4 | *east of the town Herkenbosch* |
| 5 | *west of the town of Susteren* |
| 6 | *south of the town of Valkenburg* |
| 7 | *north of the town of Eijsden* |
| 8 | *between the towns of Epen and Mechelen* |

Table 3

**Criteria:**

For a recommended precipitation station in a relevant area:

It should not be located outside a circle with a radius of 5 km from a recommended point (black triangle in Figure 9). Beyond a radius of 5 km, there may no longer be a relevant area. These criteria also apply to an operational precipitation station. If such a precipitation station has to be moved for any reason, there should still be a continuation of the established measurement series in terms of the relevant landscape within a circle with a radius of 5 km from the operational station .

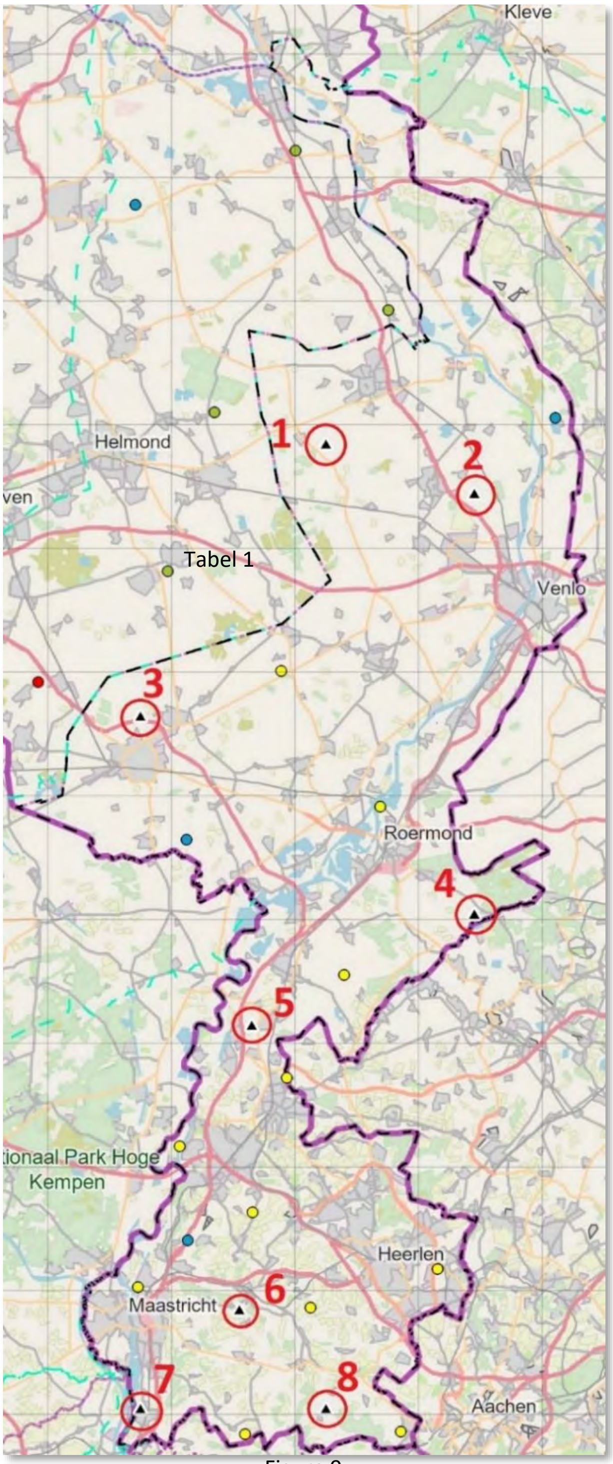


Figure 9

### 3.3 Optimal Density and Geographic Distribution in Watersheds and Flood Zones

The research area covers an area of approximately 9631 km². Currently, there are 115 precipitation stations in this area, including WL. To the east and west of the WL border, the density of precipitation stations is generally sufficient or more than adequate. In most grid squares of 10 x 10 km², one or even multiple precipitation stations are located, while in a few grid squares, no precipitation stations are present.

In the 10 km wide border area of WL, within the angular space of 180 – 225 degrees (south-southwest), roughly between coordinates X: 160,000 - 200,000 and Y: 300,000 - 307,000, the density is insufficient. There is only one station from SPW in this relevant angular space.
Thunderstorms originating in France and/or Belgium during the summer period can reach the Limburg Province from this relevant angular space. Such storms can result in substantial rainfall in a short period; 10 millimeters in half an hour is not uncommon.

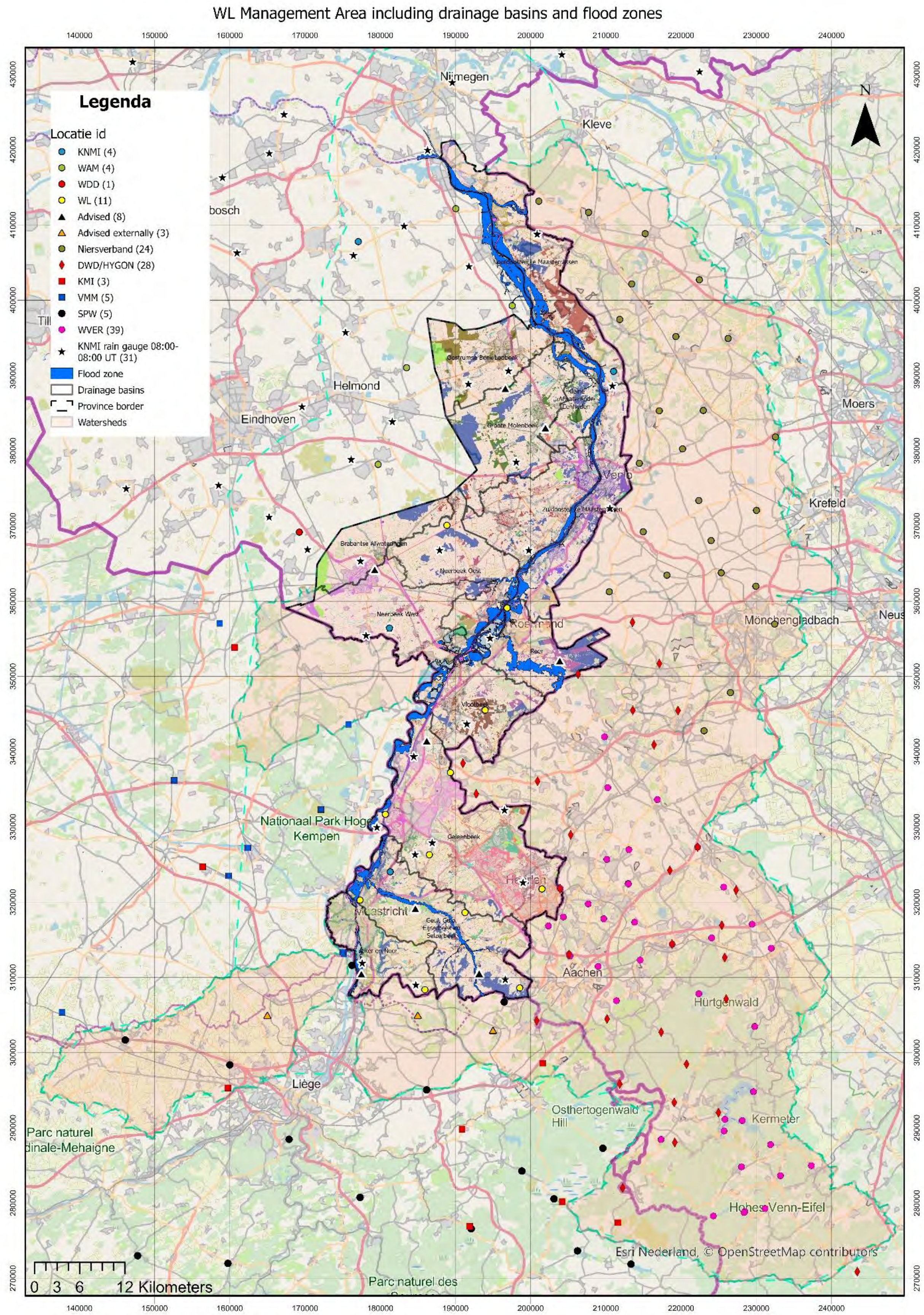
WL may consider consulting with partner SPW to establish three (3) additional precipitation stations in the above-mentioned coordinate area. The recommended precipitation stations in this coordinate area are marked with a yellow/orange triangle on the GIS map (Figure 10).

For optimal density and geographic distribution, it is recommended to establish eight (8) new precipitation stations in the WL management area. Additionally, it is advised to set up three (3) precipitation locations in the watershed and flood zone, specifically in the area to the south-southwest from WL's perspective.
This would bring the total number of stations to 135, resulting in 1 station per 70 km². This density is recommended for rough and rugged terrain, which applies to the research area. This is in contrast to a more homogeneous landscape, where one station per 100 km² is recommended.

On the GIS map (Figure 10), these virtual measurement points are indicated with yellow/orange triangles in the areas to the south and southwest outside the WL management area.

## 4- A Map of the available monitoring networks

The GIS map below gives an overview of all available precipitation stations in and outside the WL management area, including the drainage areas and flood zone.


WL Management Area including drainage basins and flood zones
Legenda
Locatie id
KNMI (4)
WAM (4)
WDD (1)
WL (11)
Advised (8)
Advised externally (3)
Niersverband (24)
DWD/HYGON (28)
KMI (3)
VMM (5)
SPW (5)
WVER (39)
KNMI rain gauge 08:00-08:00 UT (31)
Flood zone
Drainage basins
Province border
Watersheds
Nijmegen
Kleve
Helmond
Eindhoven
Moers
Krefeld
Venlo
Roermond
Mönchengladbach
Nationaal Park Hoge Kempen
Maastricht
Heerlen
Aachen
Hürtgenwald
Liège
Osthertogenwald Hill
Kermeter
Hohes Venn-Eifel
Parc naturel des
0 3 6 12 Kilometers
Esri Nederland, © OpenStreetMap contributors
Figure 10

# 5- Conclusions about adapting and supplementing the existing network, addition of disdrometers and the actions needed to realize.

In the correction of radar precipitation products using precipitation measurements from ground stations, the error due to representativeness differences between radar pixels and ground station measurements plays a dominant role. If the limitations on the spatial and temporal resolutions imposed on the correction methods are not taken into account, errors can be introduced instead of reduced.
The number and density of precipitation stations determine the outcome of correcting the radar product. The more local ground stations included, the better the local discrepancies in the radar product can be corrected.

The condition is that the quality and representativeness of the ground stations meet the WMO/KNMI standards for precipitation measurement. To assess this, the eleven (11) operational precipitation stations or locations of WL were spatially inspected in the field.

## 5.1 Quality of the Operational WL Precipitation Monitoring Network

The field research was conducted following the guidelines of KNMI, WMO, and ISO and included:

- Laser measurement of spatial angle, obstacle distance, and obstacle height from the location of the precipitation gauge on relevant obstacles. The height of these obstacles is accounted for with the installation height of the precipitation gauge (1 m);
- 360-degree scan of relevant obstacles such as trees, tree lines, shrubs, buildings, poles, and temporary objects like cars and construction materials, based on spatial angle, distance, and height of the object;
- Description of the type of obstacle(s) and the relative obstacle height (= obstacle height / obstacle distance);
- Recording inverse relative height of obstacles in a circular chart (resolution of 20 degrees) with distinction between contiguous and separate obstacles;
- Capturing quadrant photos at the intended measurement location (→ north/east/south/west);
- GPS coordinate measurement at the location, in both RD & WGS84 coordinate systems;
- Determining the WMO class (after analyzing the obstacle measurements).

*Photos were taken in all eleven measurement locations in the four cardinal directions. The N, E, S, W indications inserted on the photos may deviate by +/- 10 degrees.*

## 5.2 AMO-meteo applies the following quality criteria for precipitation stations, in accordance with KNMI/WMO-ISO standards

a. *Recommendation or usable, WMO class **1** and **2**: when objective quality requirements are met to a large extent*.
b. *Satisfactory (conditionally usable), WMO class 3: if it is possible to requalify the location as usable, for example, after pruning or cutting trees/bushes.*.
c. *Unsatisfactory or not usable, WMO class **4** and **5***.

In the obstacle charts below, the relevant obstacles are depicted as blue and/or brown spheres that have been surveyed at the measurement location. The operational precipitation gauge is located at the center of the chart. The colored rings represent distance lines, namely 1 to 5 times the obstacle height, from the precipitation gauge. The accompanying table specifies the type of obstacle.

The **Meijel** precipitation station is situated south of this location. It is located in a relatively open area, with relevant obstacles positioned at a considerable distance or deemed irrelevant. The WMO class is 1.
A point of concern (and will remain so) is the vegetation around the instrument. Within a radius of 1 to 1.5 meters, measured from the center of the precipitation gauge, the vegetation should remain low (maximum 10 to 20 cm high).

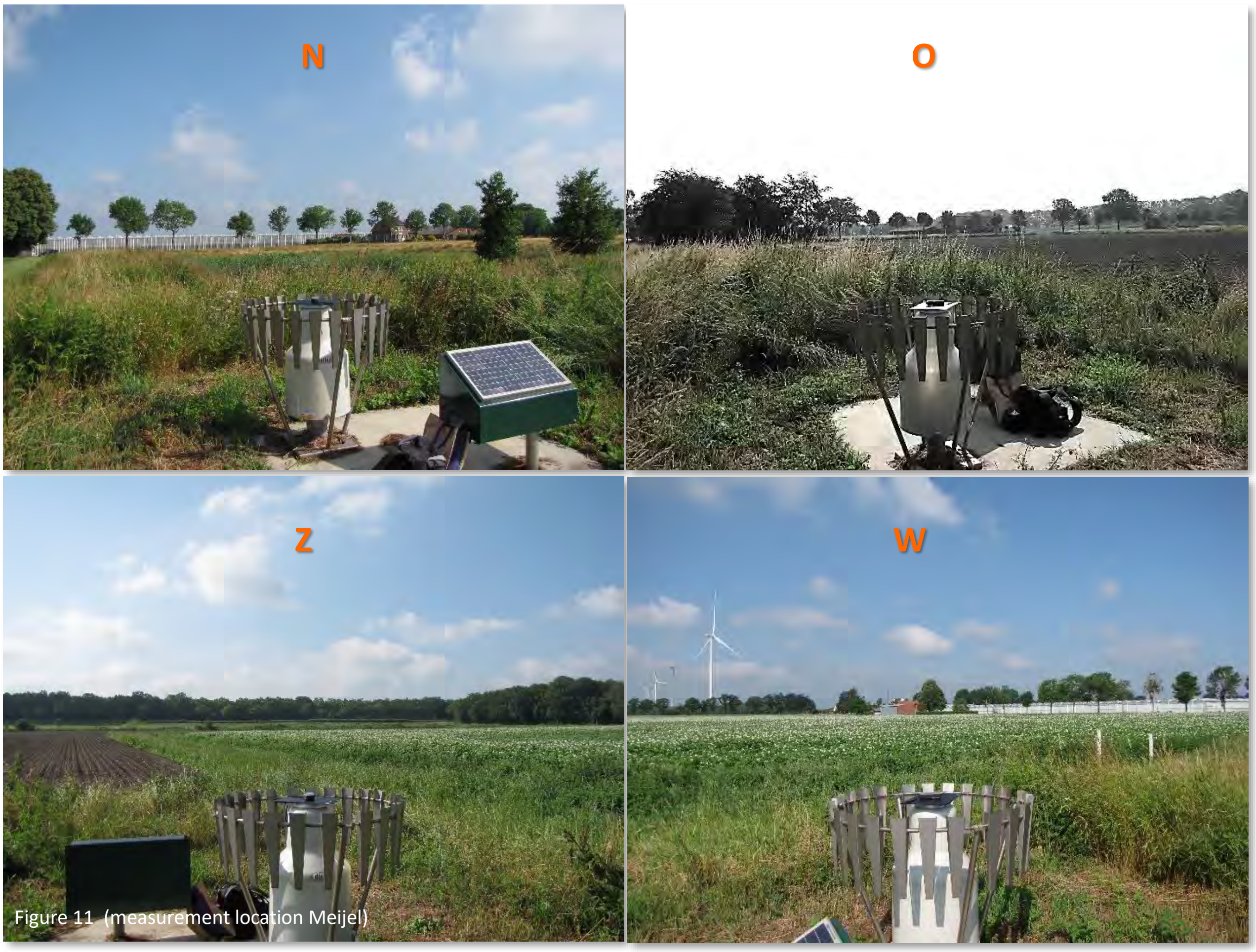
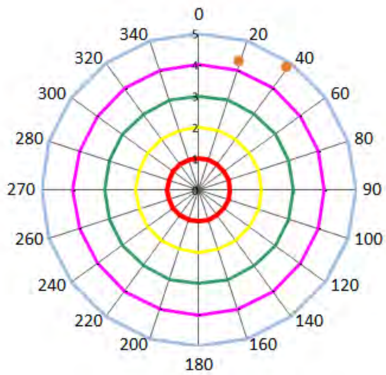



Figure 11 (measurement location Meijel)




Graph 1

| Meijel | Landscape: Meadow area | | | WMO class 1 | | | RD coordinates: X: 188.870 Y: 370.086 | | | measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 23-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | | | | | | | | | | |
| • | tree | | | | | | | | | |

Table 4

The RWZI **Roermond** location is situated in the Maas Valley, which includes the river and several lake areas. The precipitation gauge is positioned near the office/workshop building, located within the spatial angle of 0 - 90 degrees. The WMO classification is 2.

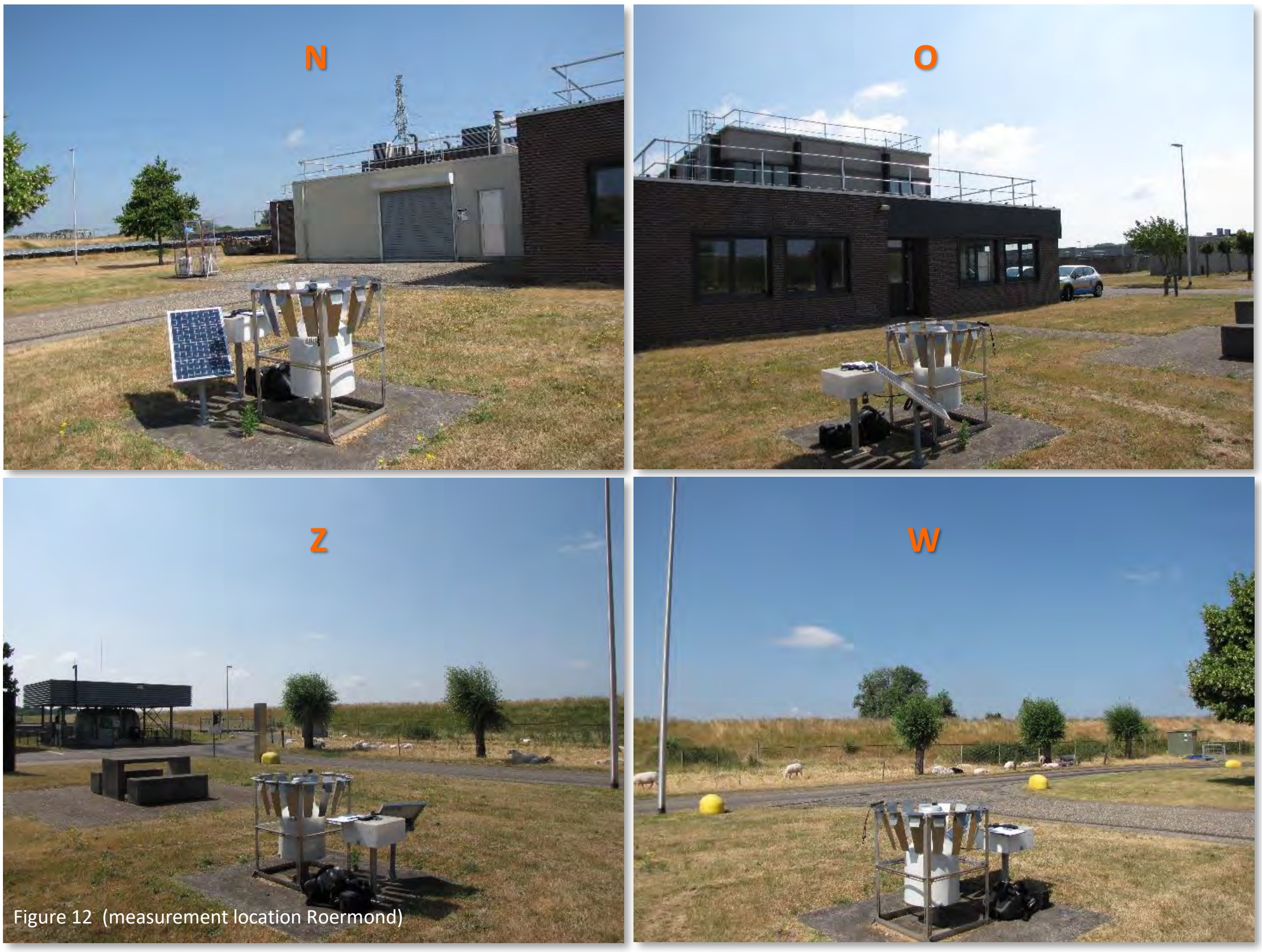
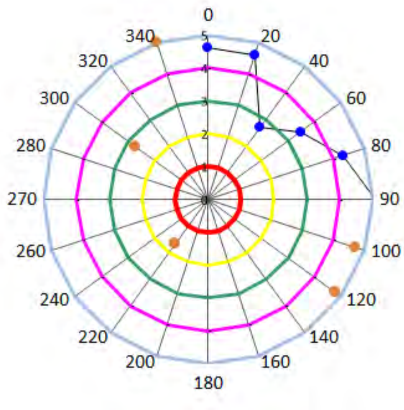



Figure 12 (measurement location Roermond)

*Remark:*

*The slender lantern palls do not affect the precipitation measurement, but for completeness they are included in the graph and table below. If applicable, this also applies to the other WL locations investigated.*




Graph 2

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Roermond* | *Landscape: Meuse Valley / urination area* | | | *WMO class 2* | | | *RD coordinates: X: 196.878 Y: 359.117* | | | *measuring height* |
| | Degrees of arc | | | | | | | | | *1 m* |
| *23-06-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | *premises (workshop)* | | | | | | | | | |
| ● | | | *lamppost* | *tree* | | *lamppost* | | *tree* | *tree* | |

Table 5

The precipitation station **Mariahoop** is located in a meadow-nature area to the east of the town of Echt. It is situated in a fairly open location, with relevant obstacles positioned at a sufficient distance or being irrelevant. The WMO class is 1. A point of attention (and one that remains) is the vegetation around the instrument. It should remain low within a radius of 1.5 meters, as measured from the center of the precipitation gauge, not exceeding a height of 10 to 20 cm.

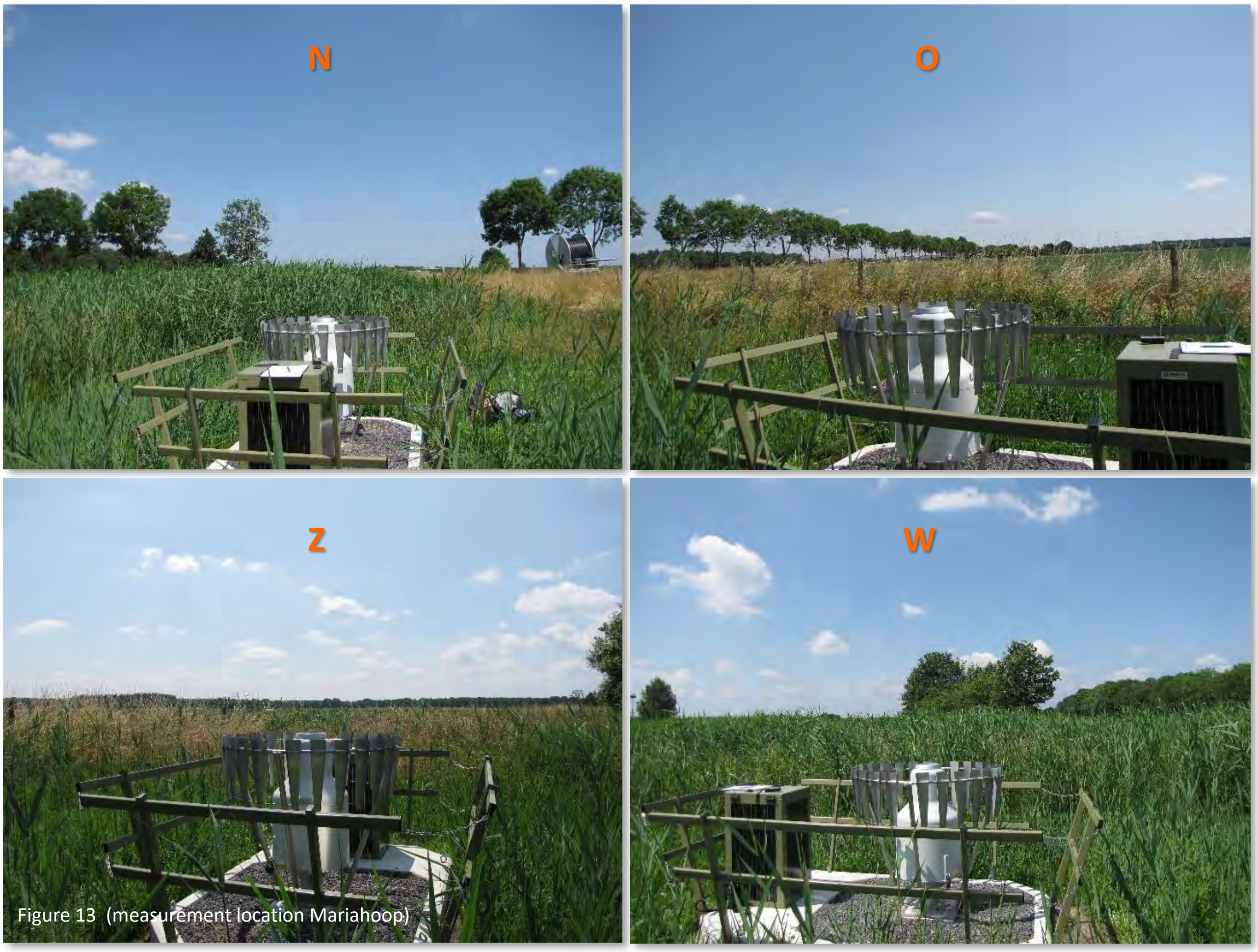
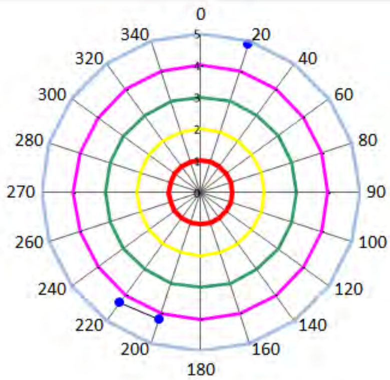



Figure 13 (measurement location Mariahoop)



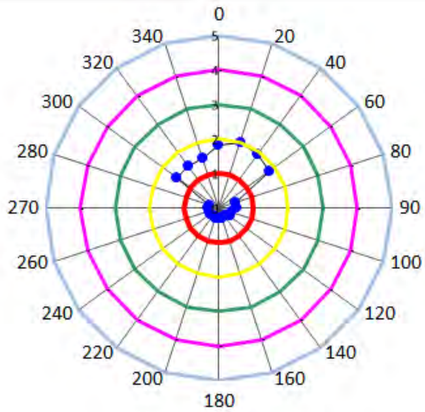

Graph 3

| *Mariahoop* | *Landscape: Meadow - nature reserve* | | | *WMO class 1* | | | *RD coordinates: X: 193.965 Y: 345.529* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *23-06-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| | *row of trees* | | | | | *trees* | | | | |
| | | | | | | | | | | |

Table 6

The precipitation station **Millen** is situated on the weir, north of the town of Sittard. It cannot be considered a representative location due to significant obstacles, mainly tall rows of trees. Within the spatial angle of 80 to 270 degrees, the obstacles are well within the minimum distance, and even within the spatial angle of 280 to 70 degrees, they fall below the minimum distance. The WMO classification is 5.


Figure 14 (measurement location Millen)




Graph 4

| Millen | Landscape: Edge of buildings / Nature res. | | | WMO class 5 | | | RD coordinates: X: 189.331 Y: 337.203 | | | Measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 23-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| ● | (high) row of trees | | | | | | | | | |
| ● | | | | | | | | | | |

Table 7

The location RWZI **Stein** is situated in the Maas Valley, between the River Maas and the Julianakanaal. The precipitation gauge is positioned between sedimentation basins 3 and 2. The instrument is (too) close to a row of trees, particularly within the spatial angle of 40 to 170 degrees. The WMO classification is 3/4.
Note: Research conducted on-site for an alternative.

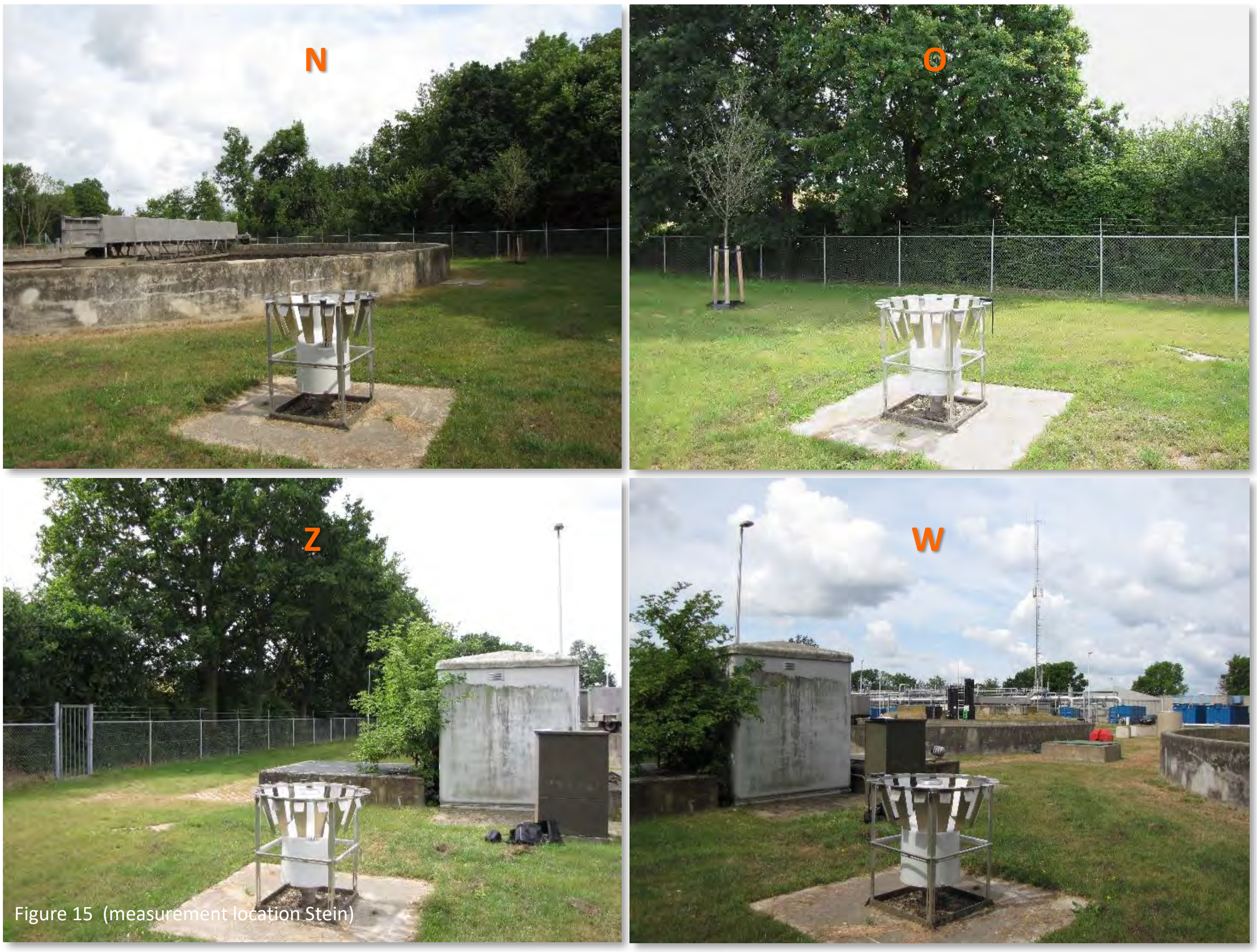
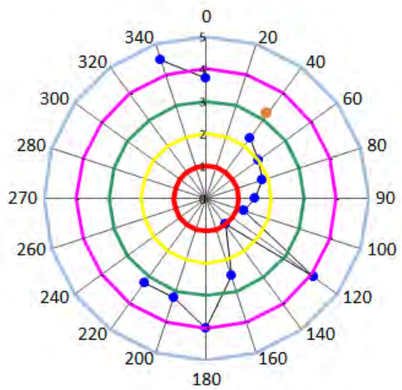



Figure 15 (measurement location Stein)



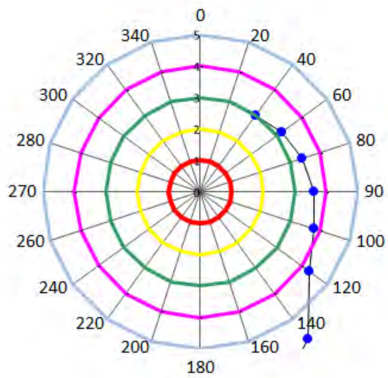

Graph 5

| Stein | Landscape: Meuse Valley | | | WMO class 3 / 4 | | | RD coordinates: X: 180.700 Y: 331.685 | | | Measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 27-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | | tree rows / building sample collection | | | | | | trees | | |
| ● | smal tree | | | | | | | | | |

Table 8

Due to relevant obstacles at the operational site that impact precipitation measurements, two alternative locations, namely **A** and **B**, were investigated on the RWZI Stein premises.
Alternative A is situated approximately 77 meters in the northwest direction from the current location.
The WMO classification is 1/2.
Class 1 for the spatial angle 80 - 40 degrees, class 2 for the spatial angle 40 – 80.

Figure 16 (alternative measurement location A – Stein)



Graph 6

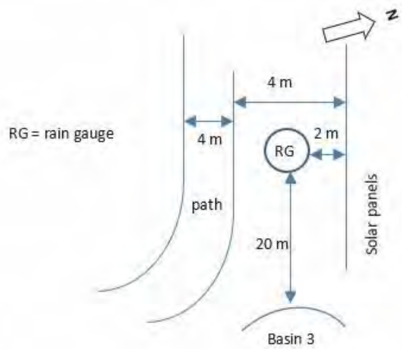


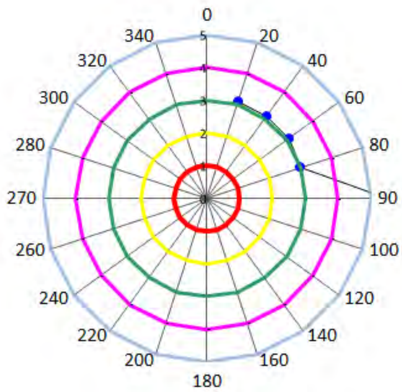
Figure A

| *Stein* | *Landscape: Meuse Valley* | | | *WMO class 1 / 2* | | | *RD coordinates: X: 180.662 Y: 331.715* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| alternative A | Degrees of arc | | | | | | | | | *1 m* |
| *26-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| | *tree rows* | | | | | | | | | |
| | | | | | | | | | | |

Table 9

In addition to alternative location **A**, location **B** has also been examined for suitability for precipitation measurement. This location is approximately 32 meters to the west of the current site.
The WMO class is 1 / 2.
Class 1 for the spatial angle 85 - 20 degrees, class 2 for the spatial angle 20 – 85 degrees.

Figure 17 (alternative measurement location B – Stein)



Graph 7

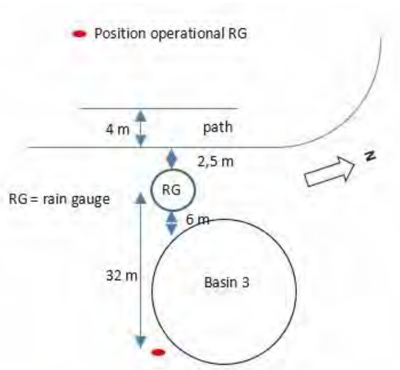


Figure B

| Stein | Landscape: Meuse Valley | | | WMO class 1 / 2 | | | RD coordinates: X: 180.671 Y: 331.696 | | | measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| alternative B | Degrees of arc | | | | | | | | | 1 m |
| 26-09-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | tree rows | | | | | | | | | |
| • | | | | | | | | | | |

Table 10

The precipitation station **Spaubeek** is located in the hilly area on the outskirts of the village. The setup is situated on the premises of the rainwater buffer 'Aan het Gebuschken'.
It features a very open arrangement, with obstacles located at more than sufficient distance or being irrelevant.
The WMO class is 1.

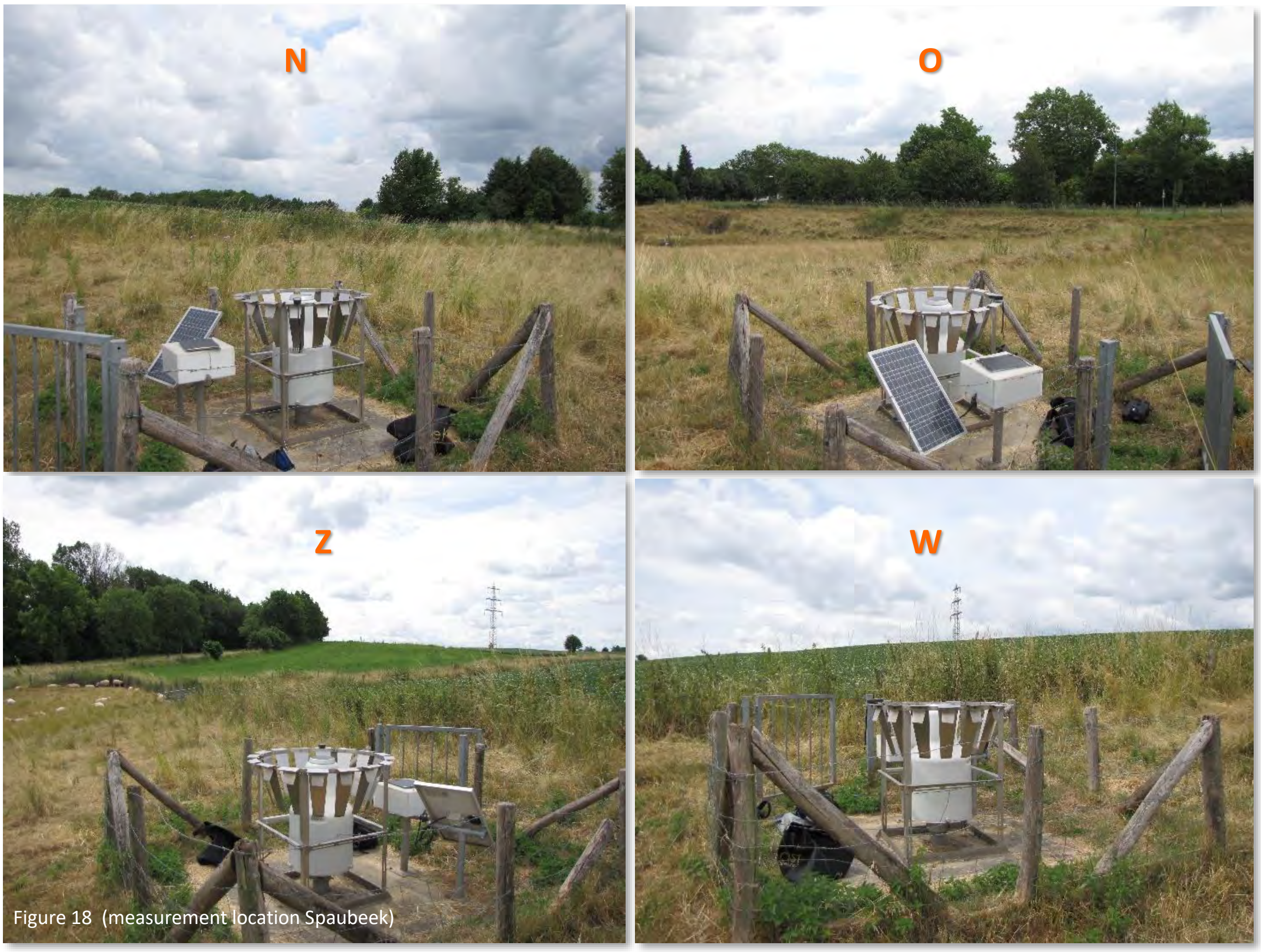
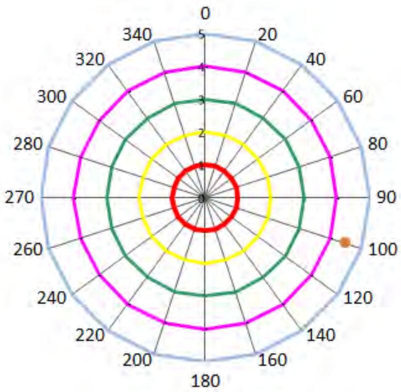


Figure 18 (measurement location Spaubeek)



Graph 8

| *Spaubeek* | *Landscape: Hilly area* | | | *WMO class 1* | | | *RD coördinates: X: 186.546 Y: 326.302* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *27-06-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | | | | | | | | | | |
| ● | | | *tree* | | | | | | | |

Table 11

The RWZI **Kaffeberg** location is situated in a small nature reserve to the NNW of the city of Kerkrade. The precipitation gauge is positioned near solar panels. Relevant obstacles, primarily rows of trees, are located within the angular range of 200 – 80 degrees.
The tree in the angular range of 243 degrees remains a point of concern. The WMO class is 2.

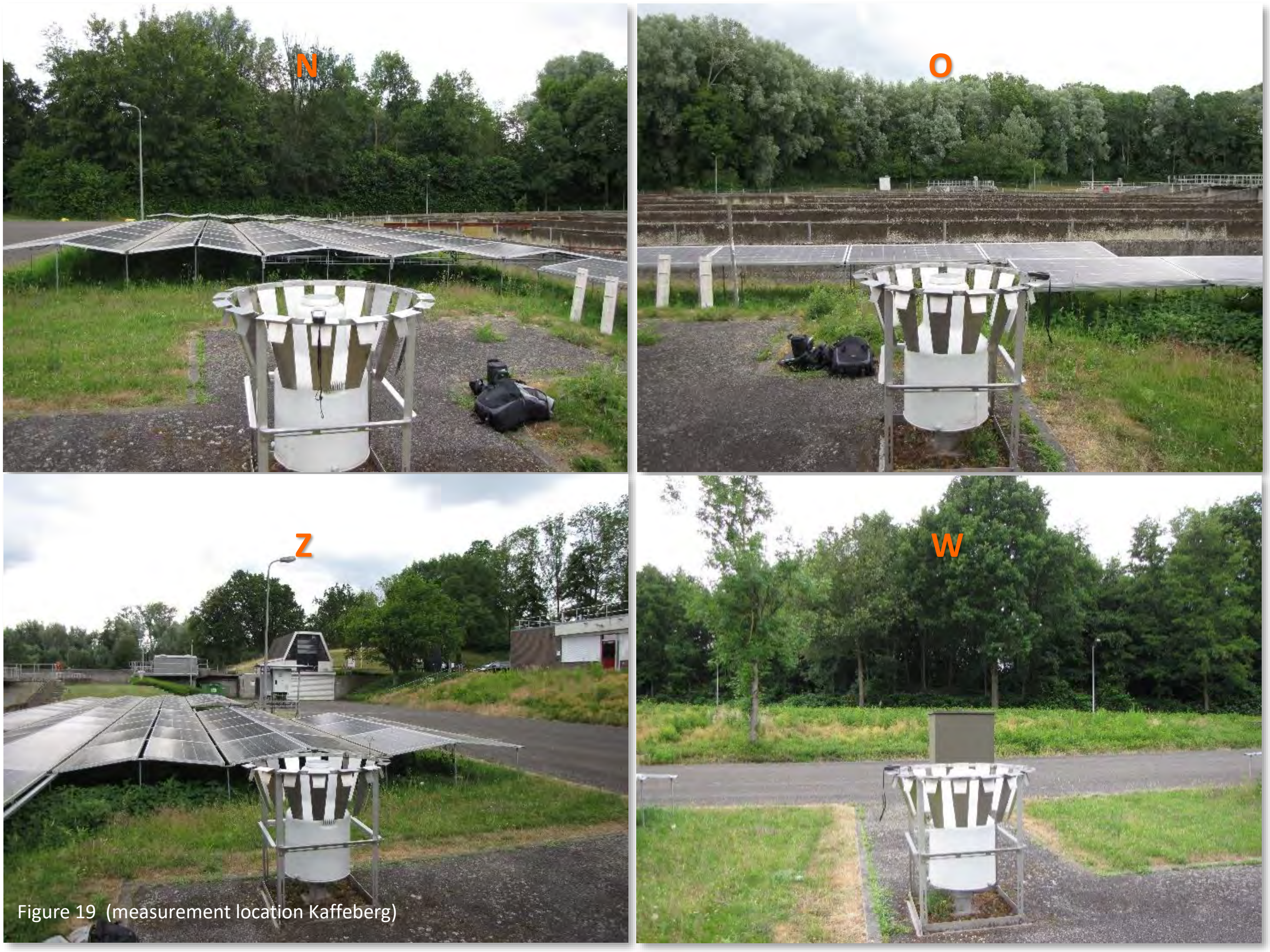
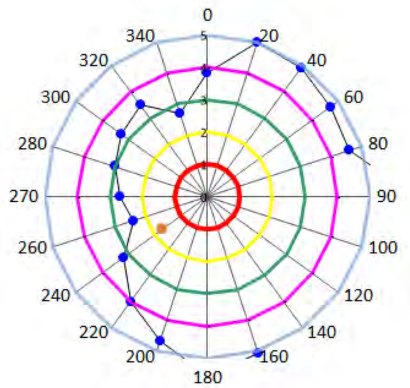


Figure 19 (measurement location Kaffeberg)



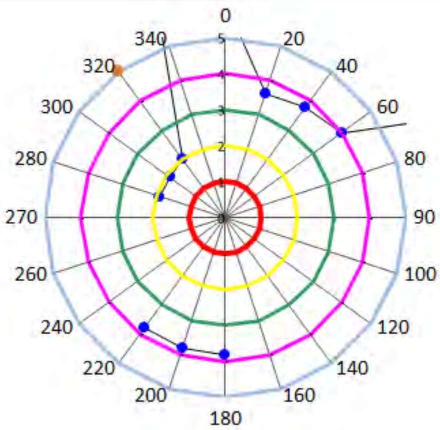

Graph 9

| Kaffeberg | Landscape: Hill nature reserve | | | WMO class 2 | | | RD coördinates: X: 201.507 Y: 321.752 | | | measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 27-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | row of trees | | | | row of trees | | | | | |
| • | | | | | | tree | | | | |

Table 12

The precipitation gauge is positioned on the grounds of 'Regenwaterbuffer St. Gillisstraat 1' in **Ransdaal**. Relevant obstacles in this hilly natural area are at a sufficient distance. A point of concern is the trees in the angular range of 280 – 320 degrees. The WMO class is 2.

Figure 20 (measurement location Ransdaal)



Graph 10

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Ransdaal* | *Landscape: Hill nature reserve* | | | *WMO class 2* | | | *RD coördinates: X: 191.273 Y: 318.623* | | | *measuring height* |
| | Degrees of arc | | | | | | | | | *1 m* |
| *27-06-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | *row of trees* | | | | *trees* | | | *tall trees* | | |
| ● | | | | | | | | *tree* | | |

Table 13

The precipitation gauge in **Noorbeek** is located on the grounds of 'Regenwaterbuffer De Peul.'
In this meadow-hilly area, obstacles are at a more than sufficient distance or are not relevant.
The WMO class is 1.

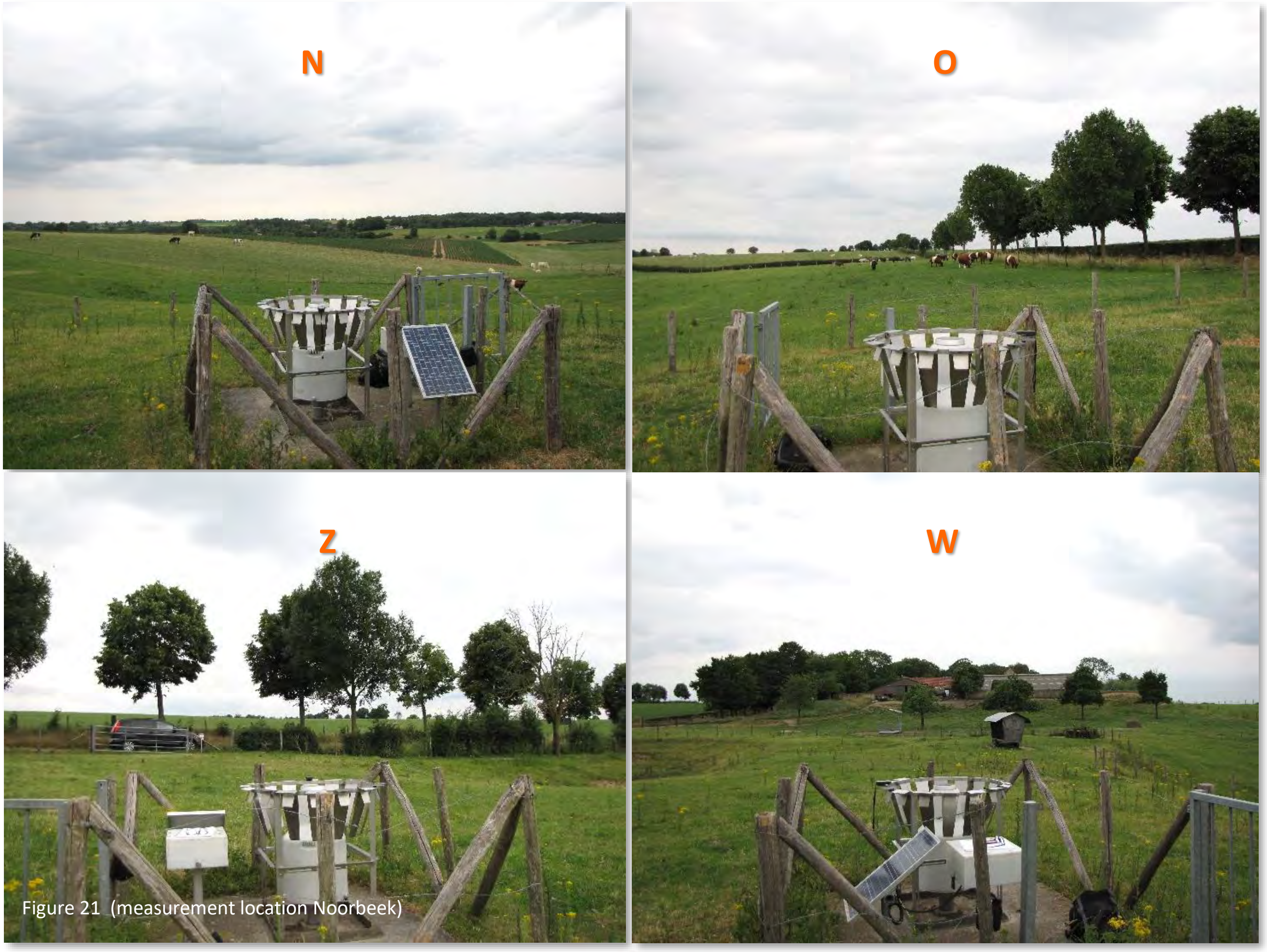
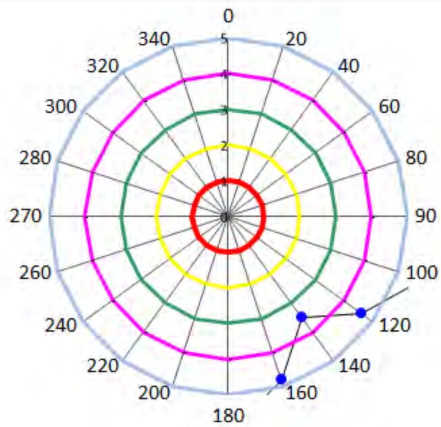



Figure 21 (measurement location Noorbeek)




Graph 11

| *Noorbeek* | *Landscape: Meadow hill area* | | | *WMO class 1* | | | *RD coördinates: X: 185.948 Y: 308.371* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *27-06-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | | | *row of trees not contiguous* | | | | | | | |
| • | | | | | | | | | | |

Table 14

The precipitation gauge is positioned on the grounds of 'Regenwaterbuffer Zieversbeek' near the town of **Vaals**. This location is in the hilly area to the south-southwest of Vaals and approximately 1.7 km north-northwest of the Three-Country Point. Relevant obstacles are at a sufficient distance.
One point of attention is the tree in the direction of 51 degrees. The WMO class is 2.

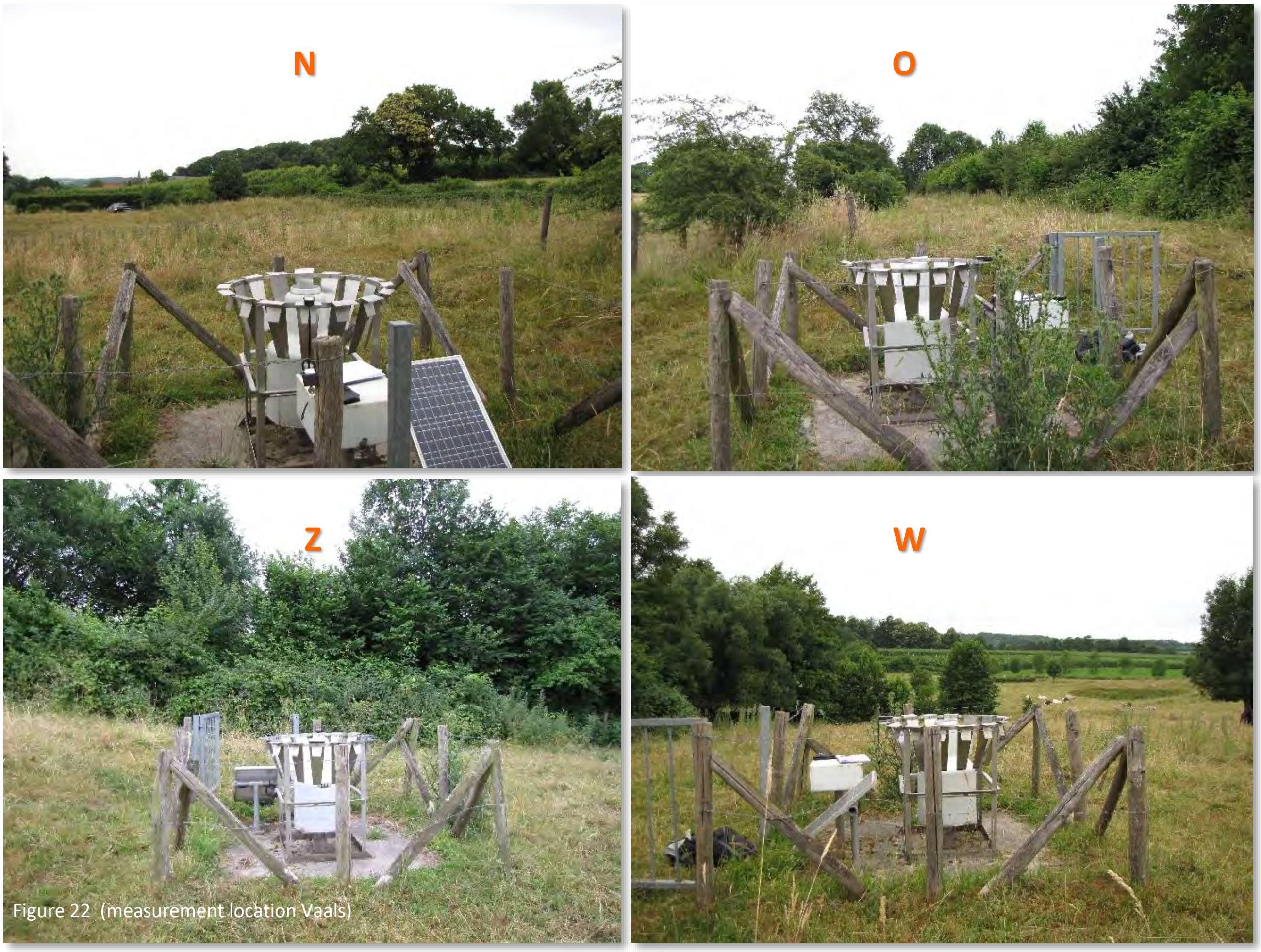
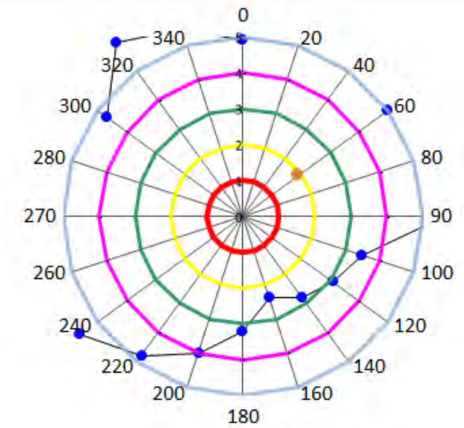



Figure 22 (measurement location Vaals)




Graph 12

| Vaals | Landscape: Hilly area | | | WMO class 2 | | | RD coördinates: X: 198.561 Y: 308.599 | | | measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 28-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | trees | | | row of trees | | | | row of trees | | |
| • | | tree | | | | | | | | |

Table 15

The RWZI **Maastricht** location is situated to the north of this city, approximately at the point where the river Maas and the Julianakanaal split. The precipitation gauge is placed near the office/workshop building and a pre-settling tank. In the sector between 40 and 62 degrees, there is a gas compressor building. The WMO class is 2.

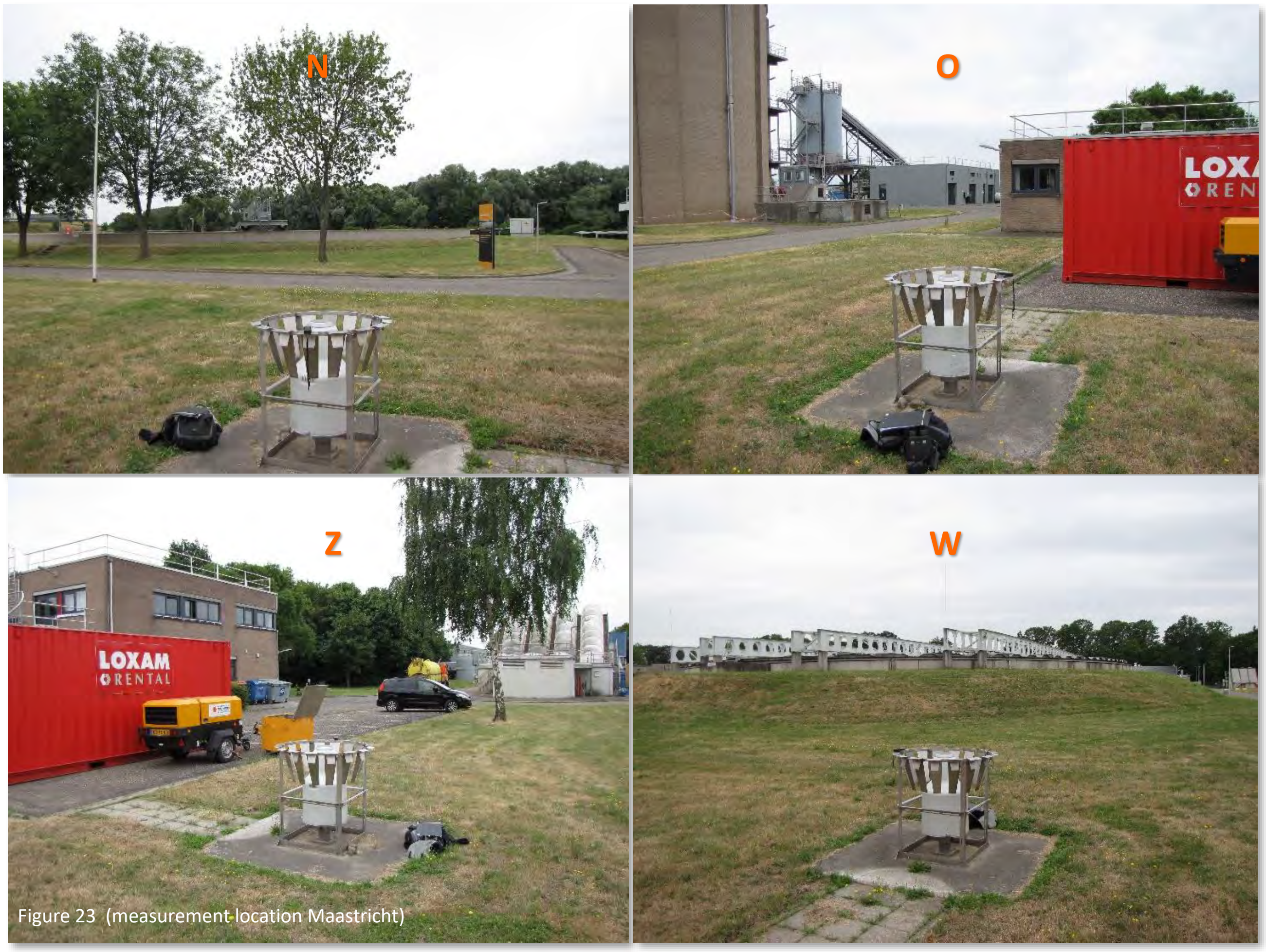
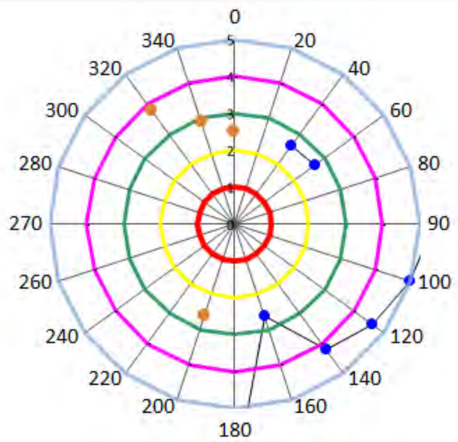



Figure 23 (measurement location Maastricht)




Graph 13

| Maastricht | Landscape: Meuse Vally / Industrial area | | | WMO class 2 | | | RD coördinates: X: 177.321 Y: 320.270 | | | measuring height |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | 1 m |
| 28-06-2023 | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— (blue) | | gas compressor | Office and workshop / trees | | | | | | | |
| ● (orange) | tree | | tree (birch) | | | | | tree | tree | |

Table 16

| Location | Spatial inspection | Description of the landscape | Precipitation gauge: Type/brand | Coordinates | | | | WMO class |
|---|---|---|---|---|---|---|---|---|
| | | | | X | Y | NB | OL | |
| Meijel | 23-6-2023 | Grassland | Pluvio² (Ott) | 188.870 | 370.086 | 51 19 08 | 05 52 23 | 1 |
| Roermond | | Lake district | | 196.878 | 359.117 | 51 13 12 | 05 59 12 | 2 |
| Mariahoop | | Pasture Natural Area | | 193.965 | 345.529 | 51 05 53 | 05 56 36 | 1 |
| Millen[1] | | Natural area | | 189.331 | 337.203 | 51 01 24 | 05 52 35 | 5 |
| Stein[2] | 27-6-2023 | Meuse Valley | | 180.700 | 331.685 | 50 58 27 | 05 45 11 | 3 / 4 |
| Spaubeek | | Hilly area | | 186.546 | 326.302 | 50 55 32 | 05 50 09 | 1 |
| Kaffeberg | | Hilly natural area | | 201.507 | 321.752 | 50 53 01 | 06 02 53 | 2 |
| Ransdaal | | Hilly natural area | | 191.273 | 318.623 | 50 51 23 | 05 54 08 | 2 |
| Noorbeek | | Meadow hill area | | 185.948 | 308.371 | 50 45 52 | 05 49 33 | 1 |
| Vaals | 28-6-2023 | Hilly area | | 198.561 | 308.599 | 50 45 56 | 06 00 17 | 2 |
| Maastricht | | Meuse Valley / Industrial Area. | | 177.321 | 320.270 | 50 52 18 | 05 42 15 | 2 |

Table 17

[1] *Relocation of the Millen precipitation meter is included in the Redevelopment Geleenbeek Millen – Nieuwstadt project.*

[2] *Two alternative locations for the precipitation meter have been determined at the treatment plant.*

## 5.3 Addition to the Operational Precipitation Measurement Network

*Research on an optimal precipitation measurement network regarding density and geographical distribution indicates that in eight (8) relevant landscapes or areas, which can have specific influence on the precipitation climate and, consequently, on the distribution of precipitation, additional precipitation stations are recommended. The total number of stations in the WL management area is currently eleven (11), which will increase to nineteen (19) after implementation.*

*Our conducted field research reveals that all eight (8) recommended precipitation stations can be realized within a circle with a radius of 5 km. The recommended eight (8) stations are plotted on a GIS map, which also shows plots of government agencies marked with colors. For the detailed assessment down to parcel level, at least two options per location were examined on suitability for precipitation measurement in the field. The best option is described.*

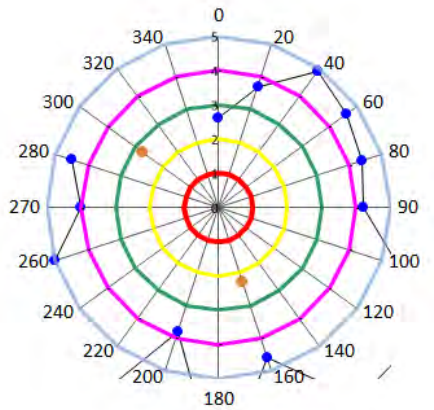
*Table 18 provides an overview of the recommended stations with their corresponding coordinates, including the entities of the respective parcels. It indicates the distance/direction in relation to a recommended coordinate point. As shown in the table, all parcels are well within the applied criteria of 5 km from a recommended measuring point. The place names have been retained for all recommended stations. Two recommended stations are located at WL's wastewater treatment plants, two on State Forestry Commission properties, one on a property owned by the Province of Limburg, one on WML's property, and two on parcels owned by a municipality.*

| Recommended station | | Owner | from recommended point | Coordinates ( X,Y) | Coordinates (WGS 84) |
|---|---|---|---|---|---|
| 1 | Leunen | WML | 4 km eastbound | X: 196.642 Y: 388.313 | NB: 51 28 56 Y: 05 59 12 |
| 2 | Horst | Staatsbosbeheer | 175 m southeastern | X: 201.970 Y: 383.073 | NB: 51 26 05 OL: 06 03 46 |
| 3 | Weert (RWZI) | WBL | 3 km southeastern | X: 179.275 Y: 364.236 | NB: 51 16 01 OL: 05 44 06 |
| 4 | Herkenbosch | Staatsbosbeheer | 1,7 km northwestern | X: 203.876 Y: 352.104 | NB: 51 09 23 OL: 06 05 09 |
| 5 | Susteren (RWZI) | WBL | 375 m western | X: 186.195 Y: 341.469 | NB: 51 03 43 OL: 05 49 56 |
| 6 | Vilt | Gemeente Valkenburg a/d Geul | 1 km northwestern | X: 184.683 Y: 319.186 | NB: 50 51 42 OL: 05 48 32 |
| 7 | Eijsden | Gemeente Eijsden - Margraten | 375 m southeastern | X: 177.502 Y: 310.500 | NB: 50 47 02 OL: 05 42 23 |
| 8 | Mechelen | Provincie Limburg | 775 m eastern | X: 193.162 Y: 310.567 | NB: 50 47 02 OL: 05 55 43 |

Table 18

The intended site is located to the south of the towns **Leunen** and Venray, and to the east of Ysselsteyn. The property belongs to the Water Supply Company Limburg (WML) and is situated approximately 4 km eastwards from the recommended location.
A representative spot for the precipitation gauge has been identified on the WML premises. Obstacles: at a sufficient distance. The WMO class is 2.

Figure 24 (recommended location Leunen)



Graph 14

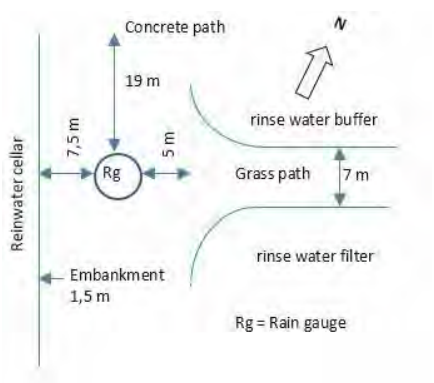


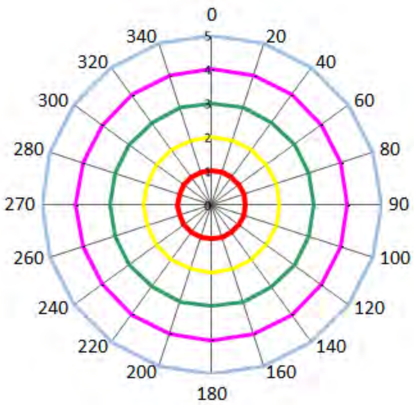
Figure C

| *Leunen* | *Landscape: Nature- Forest area* | | | *WMO class 2* | | | *RD coördinates: X: 196.642 Y: 388.313* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *09-10-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | *row of trees* | | | | | | *rows of trees* | | | |
| • | | | | *tree* | | | | *tree* | | |

Table 19

The intended forest-nature area is situated to the southeast of **Horst** and to the southwest of Reulsberg. The property is owned by ''Staatsbosbeheer'' and is located approximately 2.9 km southwest from the recommended location. A representative spot for the precipitation gauge has been identified on the ''Staatsbosbeheer'' grazing grounds.
Obstacles: at more than sufficient distance or not relevant. The WMO class is 1.

Figure 25 (recommended location Horst)



Graph 15

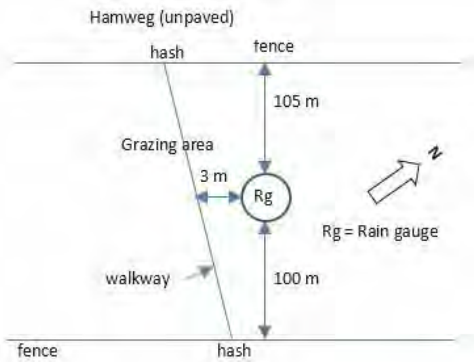


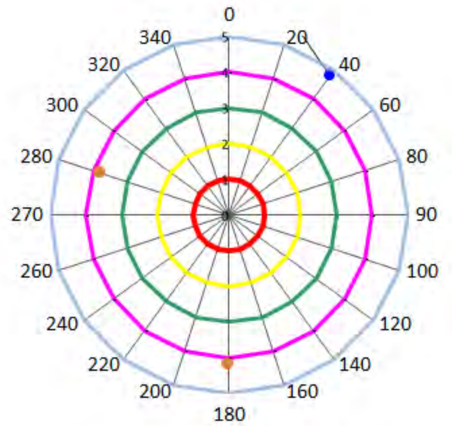
Figure D

| *Horst* | *Landscape: Nature reserve* | | *WMO class 1* | | | *RD coördinates: X: 201.970 Y: 383.073* | | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *26-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| | | | | | | | | | | |
| | | | | | | | | | | |

Table 20

The RWZI **Weert** is situated along the Zuid Willemsvaart, to the north-northeast of the city center, approximately 3 km southeast of the intended location. A representative spot for the precipitation gauge has been identified within the premises of the RWZI.
Obstacles: at a more than sufficient distance or not relevant. The WMO class is 1.

Figure 26 (recommended location Weert)



Graph 16

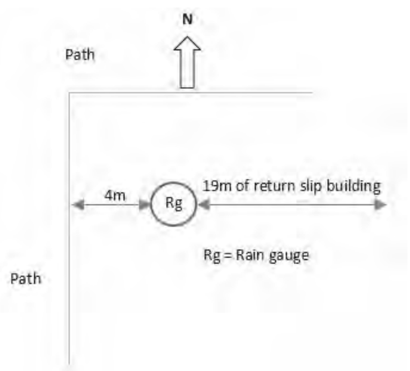


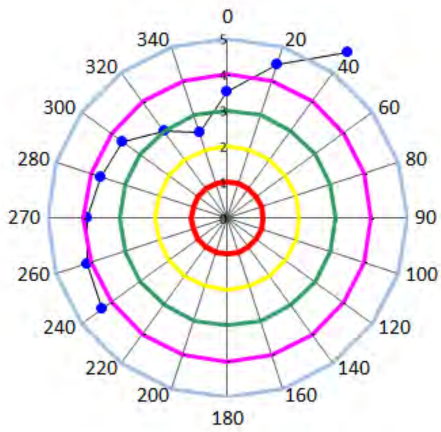
Figure E

| *Weert* | *Landscape: Edge of urban area* | | | *WMO class 1* | | | *RD coördinates: X: 179.275 Y: 364.236* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *07-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| | *slip pumping* | | | | | | | | | |
| | | | | | *lamppost* | | *lamppost* | | | |

Table 21

The Meinweg location is situated to the east of the town of **Herkenbosch**, within the Meinweg National Park. This area is owned by Staatsbosbeheer (SBB). The intended spot is located 1.7 km in the northwest direction from the recommended location. A representative location for a precipitation gauge has been determined here. The WMO class is 1/2. Class 1 for the spatial angle 10 - 300 degrees, class 2 for the spatial angle 300 - 10 degree.

Figure 27 (recommended location Herkenbosch)




Graph 17

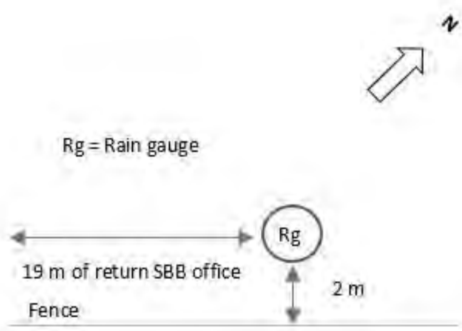


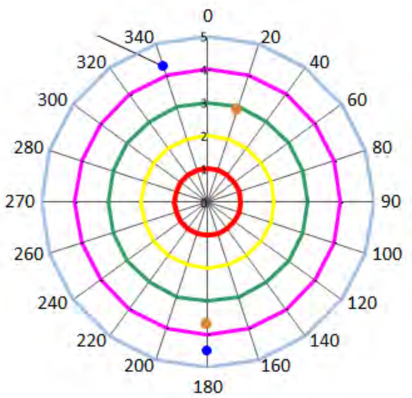

Figure F

| *Herkenbosch* | *Landscape: Forest Area National Park* | | | *WMO class 1 / 2* | | | *RD coördinates: X: 203.876 Y: 352.104* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *07-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | *row of trees* | | | | | | *row of trees* | | | |
| • | | | | | | | | | | |

Table 22

The RWZI **Susteren** is located to the west of this town, east of the Juliana Canal, and 375 meters in the westward direction from the recommended location. A representative spot for the precipitation gauge has been identified on the premises.
Obstacles: at a more than sufficient distance or not relevant. The WMO class is 1.
Note: the distance to the first wires of the high-voltage mast is 11 meters.

Figure 28 (recommended location Susteren)



Graph 18

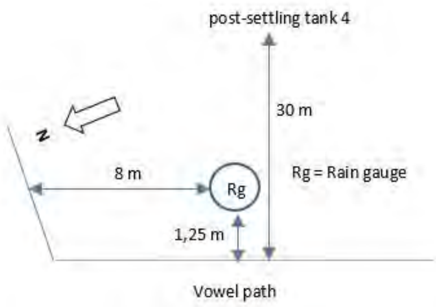


Figure G

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Susteren* | *Landscape: Meadow area near Juliana Canal* | | | *WMO class 1* | | | *RD coördinates: X: 186.195 Y: 341.469* | | | *measuring height* |
| | Degrees of arc | | | | | | | | | *1 m* |
| *07-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —•— | | | | | *Pollard willow* | | | | | |
| • | *high-voltage pylon* | | | | *high-voltage pylon* | | | | | |

Table 23

This natural area is owned by the municipality of Valkenburg aan de Geul. The terrain is located to the west of the Meertens quarry, north of the village of **Vilt**, and 1 km in the northwest direction from the recommended location. A representative spot for the precipitation gauge has been identified on the natural terrain.
Obstacles: at a more than sufficient distance or not relevant. The WMO class is 1.

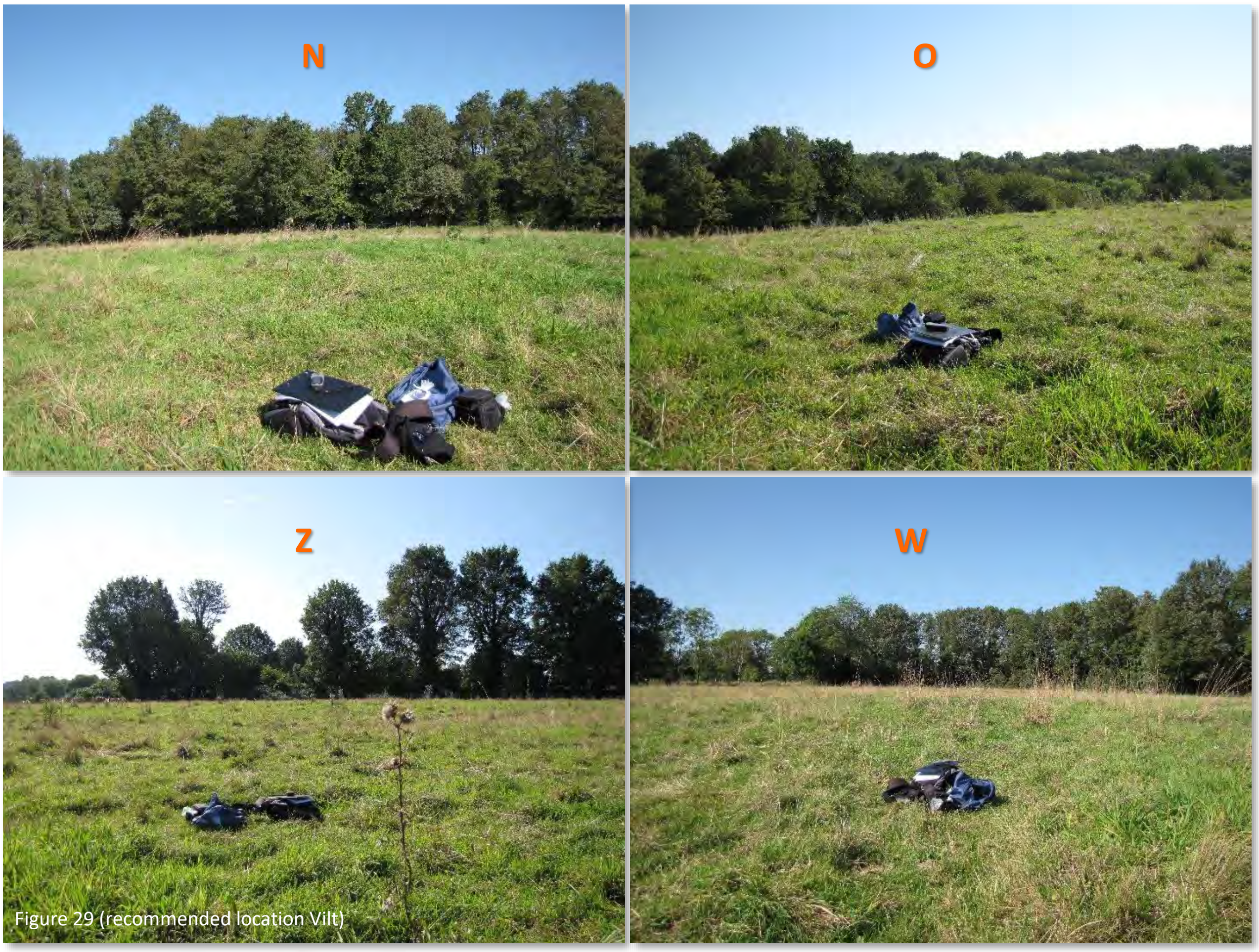
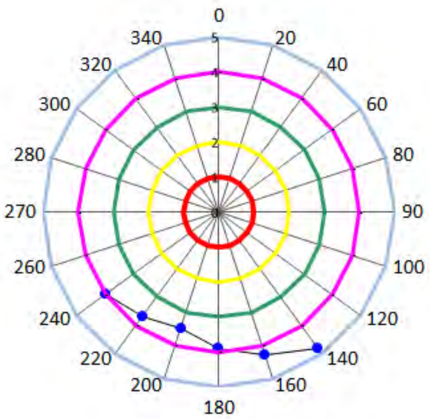


Figure 29 (recommended location Vilt)



Graph 19

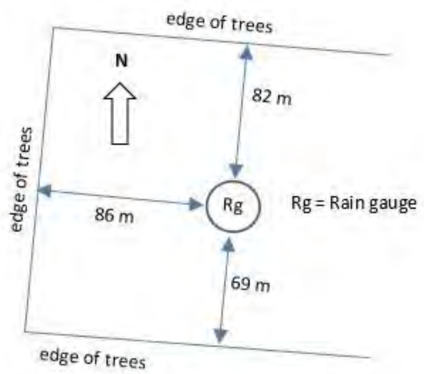


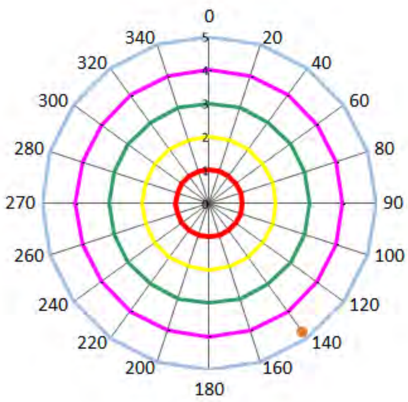
Figure H

| *Vilt* | *Landscape: Hill area* | | | *WMO class 1* | | | *RD coördinates: X: 184.683 Y: 319.186* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *08-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | | | | *row of trees* | | | | | | |
| ● | | | | | | | | | | |

Table 24

The intended site is located in the Eijsderweiden on the outskirts of the town of **Eijsden**, approximately 250 meters from the river Maas. The site is owned by the municipality of Eijsden-Margraten. A representative spot for a precipitation gauge has been identified on the site.
Obstacles: at a more than sufficient distance or not relevant. The WMO class is 1.

Figure 30 (recommended location Eijsden)



Graph 20

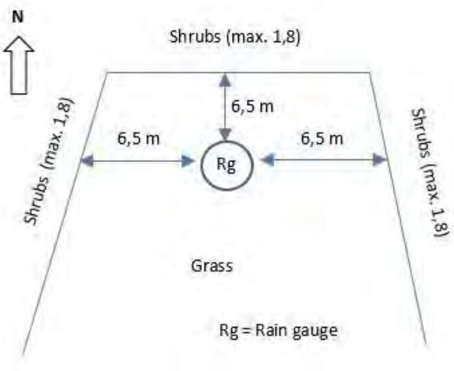


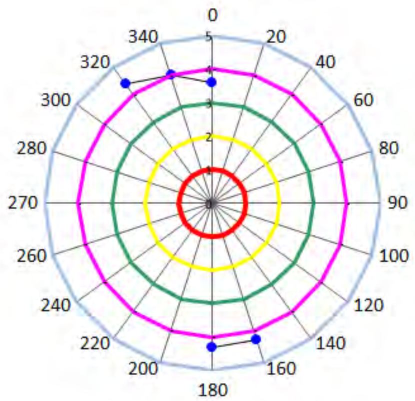
Figure I

| *Eijsden* | *Landscape: Edge of buildings / arable area* | | | *WMO class 1* | | | *RD coördinates: X: 177.502 Y: 310.500* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *26-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | | | | | | | | | | |
| ● | | | | *tree* | | | | | | |

Table 25

The intended site is owned by the province of Limburg and is currently leased to a farmer who grazes a few cows there. The site is located south of the town of **Mechelen**, northwest of Epen, and 750 meters east of the recommended location.
A representative spot for the precipitation gauge has been identified in the grass field. Obstacles: at a more than sufficient distance or not relevant. The WMO class is 1.

Figure 31 (recommended location Mechelen)



Graph 21

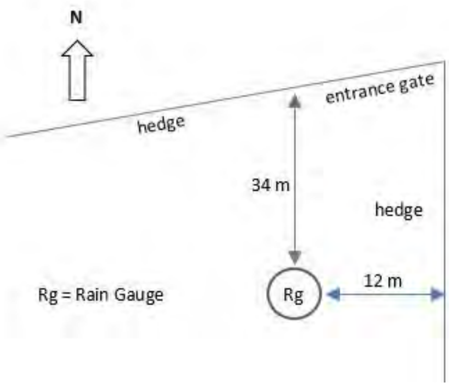


Figure J

| *Mechelen* | *Landscape: Hill area* | | | *WMO class 1* | | | *RD coördinates: X: 193.162 Y: 310.567* | | | *measuring height* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Degrees of arc | | | | | | | | | *1 m* |
| *27-09-2023* | 0-40 | 40-80 | 80-120 | 120-160 | 160-200 | 200-240 | 240-280 | 280-320 | 320-0 | |
| —●— | | | | | *trees* | | | | *trees* | |
| ● | | | | | | | | | | |

Table 26

| Advised location | Landscape | coordinates | | | | WMO class |
|---|---|---|---|---|---|---|
| | | X | Y | NB | OL | |
| Leunen[3] | *Nature forest area* | 196.642 | 388.313 | 51 28 56 | 05 59 12 | 2 |
| Horst[2] | *Nature reserve* | 201.970 | 383.073 | 51 26 05 | 06 03 46 | 1 |
| Weert[1] | *Edge of urban erea* | 179.275 | 364.236 | 51 16 01 | 05 44 06 | 1 |
| Herkenbosch[2] | *Forest area National Park* | 203.876 | 352.104 | 51 09 23 | 06 05 09 | 1 / 2 |
| Susteren[1] | *Meadow area near Juliana Canal* | 186.195 | 341.469 | 51 03 43 | 05 49 56 | 1 |
| Vilt[2] | *Hill area* | 184.683 | 319.186 | 50 51 42 | 05 48 32 | 1 |
| Eijsden[2] | *Edge of buildings / arable area* | 177.502 | 310.500 | 50 47 02 | 05 42 23 | 1 |
| Mechelen[2] | *Hill area* | 198.561 | 308.599 | 50 45 56 | 06 00 17 | 1 |

Table 27

Six (6) fall into WMO class 1, one measurement point in class 1/2, and one measurement point in class 2.

The locations Weert and Susteren are situated on WL's premises. The rest are under the management of Staatsbosbeheer, the Province of Limburg, and the municipalities of Valkenburg aan de Geul and Eijsden-Margraten.

*Additional provision around the precipitation gauge setup:*
[1] Enclosed area - no additional provision around the precipitation gauge required (230V available);
[2] Setup as in the Mariahoop station (*Figure 13*);
[3] Enclosed area - no additional provision around the precipitation gauge required (230V not available).

### 5.4 Addition of Disdrometer to the Measurement Network

In relation to a traditional precipitation gauge, the performance of two disdrometers has been compared under conditions of high precipitation intensity.
A disdrometer records, among other things, droplet size, droplet fall velocity, droplet intensity, precipitation detection (whether or not precipitation is occurring), and precipitation type (rain, drizzle, snow, hail). Precipitation amount is not measured directly but is calculated as a derivative of intensity, which does not always guarantee a correct value.
The installation height for a disdrometer is approximately 2 meters, deviating from the traditional precipitation gauge, which has a standard measuring height of 0.4 meters or 1 meter (in the case of a Pluvio precipitation gauge equipped with a wind reduction shield).

The principle of droplet detection in disdrometers bears a strong resemblance to the principle of radar precipitation estimation, involving beam reflection on droplets. Consequently, disdrometer measurements can be valuable for calibrating radar signals at different altitudes. Essentially, this involves comparing precipitation intensities from two different sources.
For the correction of radar precipitation data to precipitation amounts at the Earth's surface, data from ground-based precipitation stations are necessary. Disdrometers cannot provide these data in a sufficient quantity.

In the Netherlands, the annual precipitation amount in De Bilt gradually increased from 710 to 873 millimeters between 1900 and 2020, marking an increase of about 23% (*Figure 32*). The number of days per year with at least 10 mm of precipitation in winter and the number of days per year with at least 20 mm of precipitation in summer have risen. On average, precipitation exceeds these threshold values several times a year throughout the Netherlands. The most significant increase in these moderate extremes occurred in the coastal areas. The total number of days with more than 0.1 mm of precipitation, known as 'wet days' or 'rainy days,' remained unchanged.

Due to rising temperatures since 1950, the amount of water vapor in the air has also increased. This partially explains the rise in annual precipitation. The effect on heavy rainfall events is even more pronounced.

Observations indicate that in the most extreme downpours, the amount of precipitation per hour increases by approximately 12% per degree of warming.

Precipitation constitutes the initial phase of the hydrological cycle, encompassing all forms of water, such as rain, that fall to the Earth's surface. Understanding rainfall, its variability, and the observed patterns in both space and time are crucial for the majority of meteorological and hydrological studies.

Traditionally, rainfall amounts have been measured using a collector, gathering the volume of precipitation within a specific time period. The reference variable in this context is the depth of precipitation. In the case of constant rainfall during this time, the rainfall rate or intensity can be calculated. As the time interval shortens, the estimated intensity approaches the actual water flow reaching the ground. This estimated measure of rainfall intensity has long been accepted as sufficiently accurate for scientific and engineering applications.

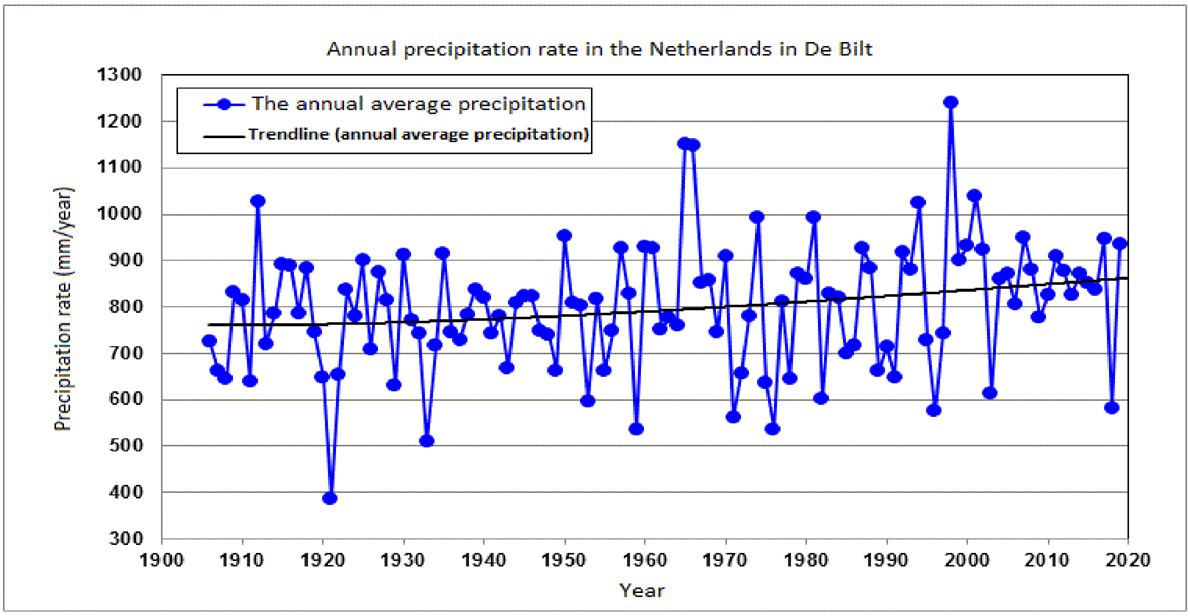


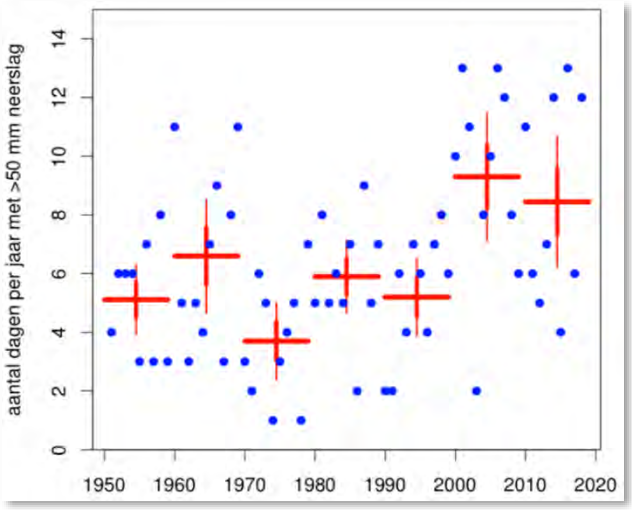

Figure 32

Due to the increased intensity of precipitation, a higher quality of rainfall intensity data is necessary. The interpretation of rainfall patterns, modeling and predicting precipitation events, and the technical applications in meteorology all rely on the analysis of finely recorded rainfall intensity data. According to the IPCC, it is highly likely that precipitation extremes will increase. All KNMI (Royal Netherlands Meteorological Institute) scenarios align with this projection. In all scenarios, the average amount of rainfall on days with heavy rain increases in summer due to more intense downpours. For winter, all scenarios indicate that the amounts of rainfall during prolonged periods of heavy precipitation will increase and change approximately in proportion to the average winter rainfall total.

The expected rise in temperature in the KNMI climate scenarios implies that extreme rainfall can also increase on a daily basis as well as on an hourly basis. The hourly rainfall intensity during extreme summer showers will probably increase more significantly than the extremes of daily rainfall amounts. KNMI refers to 'heavy rain' when the precipitation reaches 50 mm/day or more during the summer months of June, July, and August. However, in recent years, such quantities have also been observed more frequently in the months of May, September, and October. This is why KNMI also counts the number of days with heavy rainfall per year.

Figure 33 →

The number of days with heavy precipitation (>50 mm) is represented by the blue dots, indicating the count for each year. The red horizontal lines denote the averages over a 10-year period. The vertical lines represent 1 (thick line) or 2 (thin line) times the standard deviation in the estimate of the mean.




## 5.5 Comparison between Thies LPM and OTT Parsivel2 Disdrometers

The Laser Precipitation Monitor (LPM) from Thies GmbH & Co. KG utilizes a laser beam of 780 nm wavelength, averaging 228 mm in length, 20 mm in width, and 0.75 mm in thickness. This results in a sample area of 45.6 cm². Geometrical deviations from this standard are reported by the manufacturer for each specific disdrometer. For instance, the sampling areas of the two devices used in this comparison are approximately 46.65314 cm² and 49.04051 cm². The LPM registers particles with a diameter of 0.16 mm and precipitation rates from 0.005 mm $h^{-1}$ upwards. Thies's technical documentation states that size and speed measurements are "checked for plausibility" to prevent issues such as edge events. This implies that certain particles are filtered out, although the details of this procedure are not specified. From the raw particle data, various bulk variables ("PSVD moments") are internally integrated by the device's firmware. Droplet diameters and speeds are then grouped into 22 and 20 classes, ranging between 0.125 and 9 mm and between 0 and 12 m $s^{-1}$, respectively (*see table 28*).

The OTT Parsivel2, developed by OTT Hydromet, operates on the same measurement principle as the LPM. Both disdrometers belong to the second generation. The Parsivel2 uses a laser beam with a wavelength of 780 nm, measuring on average 180 mm in length, 30 mm in width, and 1 mm in thickness. The manufacturer does not provide information about deviations from these values.

The sampling area for both disdrometers was 54 cm². The OTT Parsivel2 registers particles with a diameter of 0.2 mm and precipitation rates from 0.001 mm $h^{-1}$ upwards. The measured particles are stored in drop diameter and fall speed bins within a matrix of 32 × 32 with uneven intervals, ranging from 0 mm diameter to 26 mm and from 0 to 21.4 m $s^{-1}$ (see table 26). Parsivel's technical documentation notes that the device filters out edge events, although the exact details of this procedure are not provided. Battaglia et al. (2010) mention that the latest Parsivel units incorporate two additional photodiodes at the edge of the laser beam to detect and remove edge events, but the manufacturer does not provide specific information on this. Besides filtering out edge events, Löffler-Mang and Joss (2000) state that a correction for the effective sample area is applied depending on the particle size. *Table 28* shows the classification of particles based on equi-volume diameter (D) and fall speed (V) bins for each type of disdrometer.

| Size bins (mm) | | Velocity bins (m s$^{-1}$) | |
|---|---|---|---|
| Thies | Parsivel | Thies | Parsivel |
| | 0.000–0.125* | | 0.0–0.1 |
| 0.125–0.250 | 0.125–0.250* | 0.0–0.2 | 0.1–0.2 |
| 0.250–0.375 | 0.250–0.375 | 0.2–0.4 | 0.2–0.3 |
| 0.375–0.500 | 0.375–0.500 | 0.4–0.6 | 0.3–0.4 |
| 0.500–0.750 | 0.500–0.625 | 0.6–0.8 | 0.4–0.5 |
| 0.750–1.000 | 0.625–0.750 | 0.8–1.0 | 0.5–0.6 |
| 1.000–1.250 | 0.750–0.875 | 1.0–1.4 | 0.6–0.7 |
| 1.250–1.500 | 0.875–1.000 | 1.4–1.8 | 0.7–0.8 |
| 1.500–1.750 | 1.000–1.125 | 1.8–2.2 | 0.8–0.9 |
| 1.750–2.000 | 1.125–1.250 | 2.2–2.6 | 0.9–1.25 |
| 2.000–2.500 | 1.250–1.500 | 2.6–3.0 | 1.03–1.2 |
| 2.500–3.000 | 1.500–1.750 | 3.0–3.4 | 1.2–1.4 |
| 3.000–3.500 | 1.750–2.000 | 3.4–4.2 | 1.4–1.6 |
| 3.500–4.000 | 2.000–2.250 | 4.2–5.0 | 1.6–1.8 |
| 4.000–4.500 | 2.250–2.575 | 5.0–5.8 | 1.8–2.05 |
| 4.500–5.000 | 2.575–3.000 | 5.8–6.6 | 2.05–2.4 |
| 5.000–5.500 | 3.000–3.500 | 6.6–7.4 | 2.4–2.8 |
| 5.500–6.000 | 3.500–4.000 | 7.4–8.2 | 2.8–3.2 |
| 6.000–6.500 | 4.000–4.500 | 8.2–9.0 | 3.2–3.6 |
| 6.500–7.000 | 4.500–5.125 | 9.0–10.0 | 3.6–4.1 |
| 7.000–7.500 | 5.125–6.000 | > 10.0 | 4.1–4.8 |
| 7.500–8.000 | 6.000–7.000 | | 4.8–5.6 |
| > 8.000 | 7.000–8.000 | | 5.6–6.4 |
| | 8.000–9.000 | | 6.4–7.2 |
| | 9.000–10.250 | | 7.2–8.2 |
| | 10.250–12.000 | | 8.2–9.6 |
| | 12.000–14.000 | | 9.6–11.2 |
| | 14.000–16.000 | | 11.2–12.8 |
| | 16.000–18.000 | | 12.8–14.4 |
| | 18.000–20.000 | | 14.4–16.4 |
| | 20.000–23.000 | | 16.4–19.2 |
| | 23.000–26.000 | | 19.2–21.4 |

Table 28

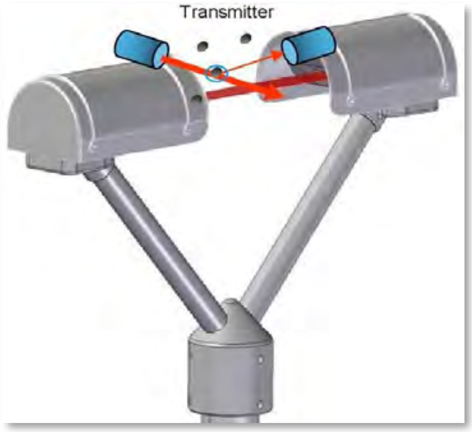



Figure 34 Thies Clima LPM

Figure 35 OTT Parsivel2

By reading the data telegrams generated by the Thies LPM and OTT disdrometers, one-minute time series of relevant variables could be created. These variables include PSVD matrices (Ni,j), bulk variables (P, R, NP, ND, Z, E), SYNOP codes, and status and error flags. An exception was the Thies disdrometers, which did not calculate kinetic energy E.

In contrast, the Parsivel provides kinetic energy expressed in joules, meaning it is divided by the sampling area and the amount of precipitation to calculate E.

$$P = \frac{4}{3}\pi \sum_{i,j} \left( \frac{1}{A_i} N_{i,j} \left( \frac{D_i}{2} \right)^3 \right), \quad 1$$

$$R = \frac{P}{\Delta t}, \quad 2$$

$$\mathrm{NP} = \sum_{i,j} N_{i,j}, \quad 3$$

$$\mathrm{ND} = \frac{1}{R\,\Delta t} \sum_{i,j} \left( \frac{1}{A_i} \frac{N_{i,j}}{V_j} \right), \quad 4$$

$$Z = \log \left( \frac{1}{\Delta t} \sum_{i,j} \left( \frac{1}{A_i} N_{i,j} \frac{D_i^6}{V_j} \right) \right), \quad 5$$

$$E = \frac{4}{3}\pi \frac{\rho}{P} \sum_{i,j} \left( \frac{1}{A_i} N_{i,j} \left( \frac{D_i}{2} \right)^3 \frac{V_j^2}{2} \right), \quad 6$$

Figure 36

In the above figure, ρ represents the density of water (1000 kg/m³), Di stands for the average diameter of class i, Vj represents the average velocity of speed class j, and Δt represents the sampling frequency (s). The effective sampling area, Ai (m²), depends on the particle size because particles must be entirely within the light beam to be detected correctly.

Therefore, it holds that:

$$A_i = A\left(1 - \frac{D_i}{2w}\right), \qquad (1)$$

Figure 37

In the above passage, it is discussed how the effective sampling area (A) of the disdrometer is related to the width of the laser beam (w). As observed, the effective sampling area decreases as the droplet size increases. The size of the applied correction is inversely proportional to W.
The two analyzed types of disdrometers exhibited different Particle Size Velocity Distribution (PSVD) spectra for the same precipitation events. The differences between the two devices of the same type were much smaller and compatible with random variations. Particularly, Thies devices, however, recorded a much larger number of droplets than Parsivel2, but also a much wider spread of PSVD spectra with a considerable number of droplets displaying unexpected combinations of size and speed, especially small droplets with exceptionally high velocities, which are compatible with edge events. On the other hand, Parsivel2 devices recorded fewer droplets and a PSVD spectrum much closer to the theoretical model. They also tended to underestimate the fall speed compared to both Thies and a theoretical fall model.

Differences in the PSVD spectra resulted in significant discrepancies between the two disdrometers in all bulk precipitation parameters such as rainfall intensity and quantity, particle density, radar reflectivity, or kinetic energy. These differences were found after these variables were calculated by the internal firmware of the devices as well as by the calculation from the PSVD data.
After filtering this data by considering only particles with a diameter between 0.25 and 8 mm and removing unlikely droplet size and speed pairs, and applying a correction for the effective sampling area, the size of the differences was reduced, although the trend persisted. In all cases, the differences increased with precipitation intensity, as well as the variance between devices of the same type, in line with expectations and previous studies.

The comparison between a disdrometer and a Pluvio rain gauge demonstrates that the disdrometer measures with less accuracy than the Pluvio rain gauge, typically around 10-20% compared to 5% in the lab.
As described in the section on *Adding Disdrometers to the Measurement Network*, he amount of rainfall from a disdrometer is not directly measured but is derived from the measured quantities.

Disdrometers are challenging to calibrate in the lab. This requires a drop simulator with which the bias can be verified and adjusted. However, the measurement volume is usually not homogeneous, so the measurement result depends on where the drop falls precisely. This leads to greater measurement uncertainty and more variability in the measurements compared to the catchment of the Pluvio rain gauge (and other traditional rain gauges).

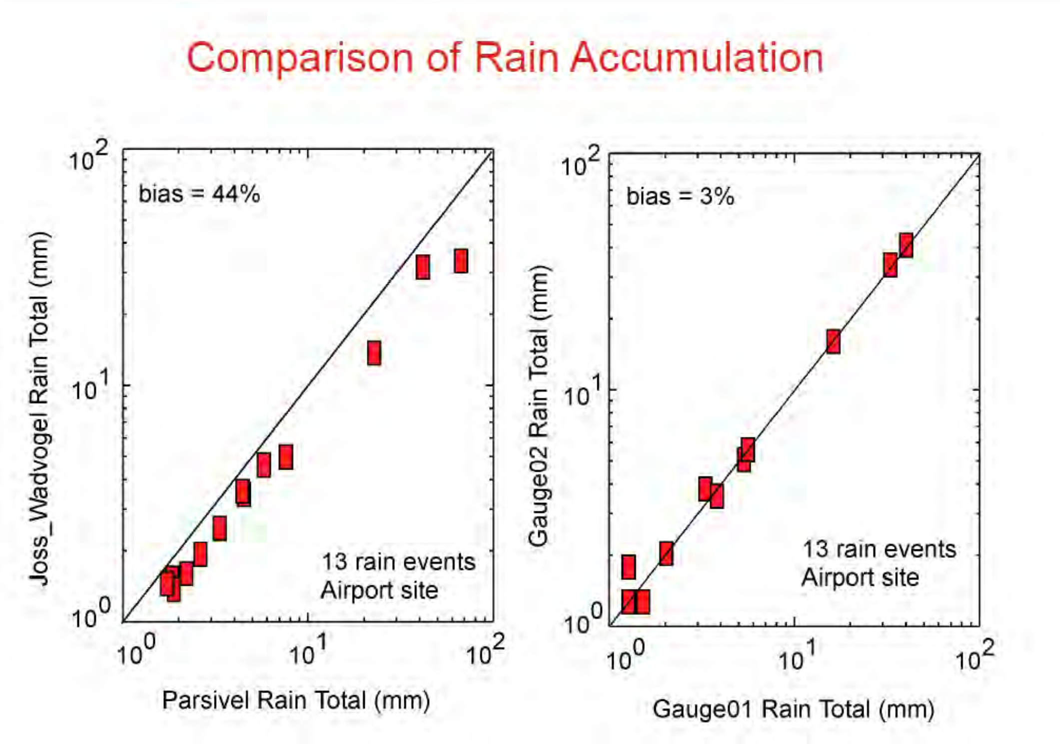



Figure 38

## 5.6 Conclusions

The total area within the research area, including WL, measures 9631 km². There are currently 115 precipitation stations in this area, resulting in a station density of approximately 1 station per 84 km². However, in the 10 km wide border area of WL, within the spatial angle of 180 - 225 degrees (south-southwest), roughly between coordinates X: 160,000 - 200,000 and Y: 300,000 - 307,000, only one station from SPW is located. To enhance coverage, it is recommended to add 3 (three) additional stations in this region.

WL's operational rainfall monitoring network currently comprises eleven (11) stations, with uneven distribution across the area. The southern part has denser coverage compared to the northern region of the Province. Within the management area, there are three AWS stations operated by KNMI. Additionally, neighboring watershed management authorities, De Dommel and Aa en Maas, operate precipitation stations, along with another KNMI AWS station. To establish a well-covered rainfall monitoring network, it is advisable to set up 8 (eight) more precipitation locations. Consequently, the station density will significantly increase from 1 station per 201 km² to 1 station per 116 km².

In the northern Maas terrace of WL, roughly between the locations Milsbeek and Well, no recommended precipitation stations are advised. The reason for this is that west of the Maas, two precipitation stations from the adjacent Waterschap Aa en Maas are situated. These are: Land van Cuijk at approximately 2.7 kilometers and Holthees at approximately 2.2 kilometers from the WL management area.

These locations utilize a type/brand of precipitation gauge that is also in use at WL. The WMO class for Land van Cuijk is 1 (partially 2), while that of Holthees is 2. By employing these neighboring stations, there is sufficient coverage. Additional WL precipitation stations in the northern Maas terrace area are therefore not deemed necessary for this reason.

Research indicates that the disdrometer, as an additional instrument in the monitoring network, does not yet meet the WMO recommendations regarding rainfall quantity. There are significant discrepancies compared to a traditional rainfall meter of the type used by WL. However, the value of a disdrometer in an existing or planned operational rainfall monitoring network lies in its capabilities for rainfall detection and calibration of radar signals at altitude.

Among the eleven (11) investigated WL locations, there is a precipitation meter of the weighing type. The Millen location falls under WMO class 5 (non-representative station). The relocation of the Millen precipitation meter is part of the Redevelopment Geleenbeek Millen – Nieuwstadt project.
Regarding the WL location Stein, classified as WMO class 3 / 4, two alternative sites were examined for suitability.

## 5.7 Concrete Recommendations:

- **Expand WL's existing monitoring network by adding eight (8) additional precipitation stations at the recommended locations.
- **For the correction of local radar products, integrate data from WL's own precipitation stations, automatic precipitation measurements from KNMI, and those from neighboring watershed management authorities and/or partner organizations. Monitor neighboring watershed stations for several months to one year in comparison with the corrected radar product before incorporating them into the correction process. If discrepancies are significant, refrain from using the respective measurement station for correction.
- **Avoid applying radar correction with ground observations at a temporal resolution shorter than 1 hour, preferably utilizing periods of at least 3 hours.
- **Include a sufficient number of radar station pairs in the correction of radar products, especially in convective weather situations, to prevent errors due to representativity differences.
- **Continuously monitor the measurement stations used for correction in comparison with the corrected radar product and calculate statistical parameters such as bias and standard deviation.
- **Monitor the availability of both radars; necessary information is present in the metadata, as the absence of a radar can significantly impact the quality of precipitation products.
- **Require all precipitation stations to report based on real-time data with a high temporal resolution of five (5) minutes.
- **Conduct annual maintenance checks on all precipitation meters at WL locations.
- **Perform a spatial inspection of the site environment at each location biannually (once every 24 months).
- **Consider maintaining a backup precipitation meter in stock. In the event of operational meter failure, the backup unit can be deployed immediately. This approach ensures that the data series from the respective station is only interrupted for a 'short period.

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