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Correction of rainfall series in the Netherlands resulting from leaky rain gauges

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De Bilt, 2020 | Technical report; TR-387

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Contents

Preface

In the period 2012-2014 new rain gauges were installed on the 320 stations of the KNMI manual daily rainfall network. In the beginning of 2017 it turned out that part of the gauges were probably leaky as a result of a design fault. As the rainfall of this network serves as the reference rainfall for the Netherlands, immediate action was needed.

Within two months all stations were inspected. During the inspections the (potential) leakiness of the rain gauge at each station was determined. All rain gauges were sealed on site to prevent further leakage. Part of the rain gauges were examined at KNMI in De Bilt and a field experiment was set up to study the problem in more detail. In addition, a project was started to correct the rainfall series of stations with potentially leaky gauges.

This report describes the work needed for the correction of the daily rainfall series of stations with leaky rain gauges.

1. Introduction

1.1. Problem description

KNMI operates a network of 320[1] manual rain gauges in the Netherlands. Volunteers measure rainfall daily at 8:00 UTC. In the period April 2012 - April 2014 new rain gauges were installed replacing the old ones at all 320 locations. The new gauges should be exact copies of the old ones with only one difference: the height of the reservoir was increased to contain 150 mm of rainfall compared to the 115 mm of rainfall previously. The poles carrying the gauge were lowered 3.5 cm to leave the rim at the operational height of 40 cm above ground level[2].

Photo 1 Left: KNMI manual rain gauge (collecting surface 200 cm^2) consisting of a reservoir (lower part) and a funnel (upper part). A ring with a height of 5 cm is attached to the funnel to clamp the funnel on the reservoir. The rim is at a height of 40 cm above ground level. Right: Funnel and reservoir taken apart and the measuring glass. Before each measurement the funnel is removed from the reservoir and the reservoir is emptied in the measuring glass.

In the beginning of 2017 it turned out that a large part of the rain gauges had become leaky due to a design fault. Stations with leaky rain gauges measured too much rainfall compared to stations with non-leaky gauges. In contrast to the old rain gauges, the ring on the funnel of the new gauge was glued to the funnel instead of soldered. This was not a durable approach. Some of the rings became loose and shifted upward. In addition to the rainfall falling into the funnel, now also part of the rainfall splashing against the outer side of the funnel could find its way into the reservoir. The defect funnels were repaired by the manufacturer using spot welding. Although

[1] At any time, the exact number may slightly deviate from 320. For several reasons, stations may sometimes be terminated while a successor may not or not immediately be found at the location or at another location.

[2] Because the new gauges were considered to be exact copies of the old ones, parallel measurements - comparing the old and new gauge - were not deemed necessary.

the rings were now firmly attached to the funnel, the repair caused gaps in between the welding spots. Unfortunately, by then this was not recognized as a problem. Later it became clear that the gaps could result in measuring too much rainfall. Through the gaps, rainfall splashing against the outer side of the funnel could find its way into the reservoir.

Awaiting the installation of newly fabricated gauges (without shortcomings) all 320 gauges were sealed in June-July 2017 using a special tape to prevent leakage. If sealing was not possible because of a loose and shifted ring[3], the rain gauge was replaced by another sealed gauge. At eleven stations an old type rain gauge was still being used. These were non-leaky gauges and did not need repair.

Altogether, there were basically five possibilities when the gauges were sealed in June-July 2017:

1. The new rain gauge was still in good condition and not leaky.
2. The new rain gauge was slowly becoming leaky because the glue was deteriorating, and small gaps appeared between the ring and the funnel.
3. The new rain gauge was leaky because the ring on the funnel had shifted upward and repair had not yet taken place (in practice this stage is preceded by stage 2).
4. The new rain gauge was repaired using spot welding because of a shifted ring discovered in an earlier inspection. Gaps between the welding spots could still cause the gauge to be leaky.
5. The gauge was one of the eleven non-leaky old type rain gauges.

The two main problems addressed in this report are: the identification of stations with leaky rain gauges and the subsequent correction of the daily rainfall amounts for these stations.

Photo 2: From left to right: gauge with ring shifted upward, gauge repaired using spot welding but with gaps between the welding spots, and gauge sealed with special tape.

[3] These new gauges were not yet repaired using spot welding.

1.2. Scope and objectives

The objectives of this study are (a) to identify all stations with leaky rain gauges in (part of) the 2012-2017 period, and (b) to find out how the leakiness developed with time and correct the underlying daily rainfall series.

1.3. Structure of the report

The next chapter describes how (potentially) leaky stations were identified using existing metadata and experiments. A distinction between leaky and non-leaky gauges is important as the latter can be used as a reference in the correction process. Thereafter, we describe the data used followed by a description of all steps needed in the process from identifying stations with leaky gauges to correction of the rainfall data from that station. In the results chapter we present all stations with leaky rain gauges and summarize their corrections. We end this report with a summary and conclusions.

2. Identifying leaky rain gauges

The identification of leaky rain gauges is not straightforward. As it was not feasible to bring all gauges to KNMI in De Bilt for examination, we had to test the leakiness on site before sealing the gauges. This test and a further examination of a number of potentially leaky gauges at KNMI, enabled us to make a distinction between non-leaky and potentially leaky gauges. However, this only applies to the situation at the time of the on-site leakiness test in June-July 2017. The metadata of each station had to be studied to disclose the complete history of its rain gauge. This revealed that between the placement of the new gauges in the 2012-2014 period and the leakiness test, about 100 gauges had become defect and were replaced by a spare gauge (mostly a new gauge that had become defect and was repaired thereafter by the manufacturer, but sometimes an old type gauge). A leakiness test for these gauges is obviously impossible and they had to be classified as potentially leaky for the corresponding period.

In addition to the above, a field experiment was set up at the KNMI test site in De Bilt to compare several leaky and non-leaky gauges. The results of this test give insight in the effect of leakiness on measured rainfall in the field. In addition, they provide a means to value the magnitude of the correction of the rainfall data from the leaky rain gauges.

2.1. On-site leakiness test

In June-July 2017 all 320 stations of the KNMI manual daily rainfall network (MN) were inspected. The purpose of the inspection was to perform an on-site leakiness test and to seal the rain gauge with a special tape at the station location. When a rain gauge was damaged, it was replaced by another (sealed) rain gauge from the pool of spare gauges. In the case that the ring was shifted upward, a leakiness test could not be performed on site[4], but the gauge was later examined at KNMI.


Photo 3 Left: Rain gauge funnel turned upside-down, showing a (potentially) leaky rain gauge. Right: Performing the leakiness test. Note that water is added in the space between the funnel and the ring.

We devised a simple test to determine the potential leakiness of a gauge in the field. When turned upside-down, water could be added in the space between the funnel and the ring. If water was flowing out, the gauge was

[4] As follows from the description of the leakiness test, there is space needed between the ring and the funnel to add water. This space is not available for gauges with the ring shifted upward (see also Photo 2 left picture).

considered (potentially) leaky with the magnitude of the flow being a first indication of leakiness. The procedure was as follows:

1. Place the funnel, turned upside-down, in a plastic container.
2. Use the measuring glass of the gauge to pour a volume of water equivalent to 4 mm of rain in the space between the funnel and the ring (this volume almost completely fills this space) and start a stopwatch.
3. Measure the time till all water has flown out of the space between the funnel and the ring, if this occurs within two minutes, and go to step 5. Else, go to step 4.
4. Remove the funnel from the container after two minutes and use the measuring glass to determine the amount of water in the container.
5. Calculate the leakiness in mm/min by dividing the amount of water in the container by the time it took to get the water in the container.

Of the 320 visited stations only 93 had non-leaky rain gauges. Figure 1 shows a histogram of the leakiness values of (potentially) leaky gauges. For 28 gauges the on-site leakiness test could not be done because of a shifted ring.

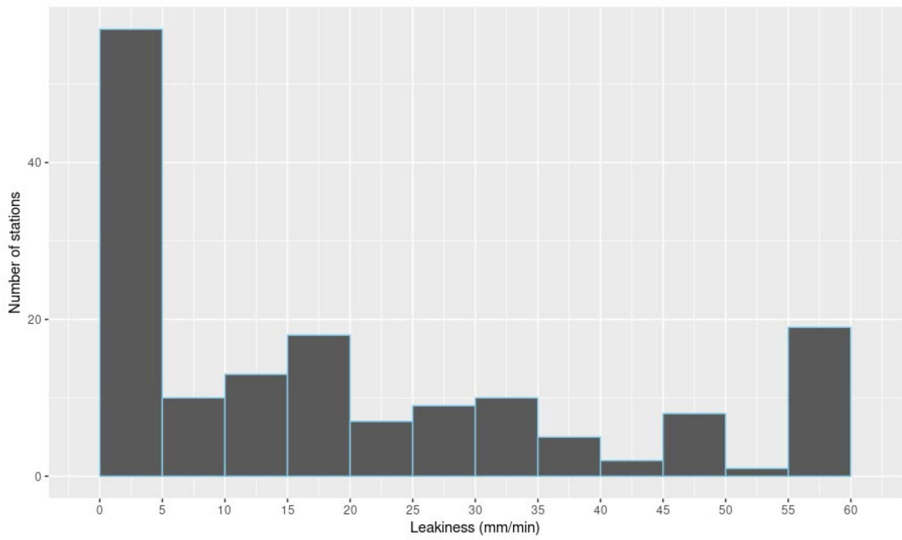

Figure 1: Histogram of the leakiness values in the on-site leakiness test. Only values > 0 mm/min are presented. Values > 60 mm/min are cut off at 60 mm/min.

2.2. Leakiness test at KNMI (shower test)

The on-site leakiness test only provides an indication of the potential leakiness of a gauge. In reality, a funnel is not turned upside-down as in the on-site test. Rain enters the reservoir when it splashes against the outer side of the funnel and finds its way into the reservoir via gaps between the funnel and the ring. In addition, for gauges with the ring of the funnel shifted upward, the direct aperture between the funnel and the reservoir is an extra possibility for the water to enter the reservoir. Although the aperture may increase the leakiness, it is considered to be too small to increase evaporation of water from the reservoir.

It is of interest to know how the leakiness found on site, with the funnel turned upside-down, relates to the leakiness that may occur in reality. We therefore designed an experiment where a selection of 59 rain gauges[5] was tested in a shower at KNMI. In the shower we attempted to mimic the situation in the field. The following procedure was followed for each gauge:

1. Place the gauge in the shower on a turning stool.
2. Use the shower head and hose to water the outside of the funnel (with an angle of about 45° with respect to the vertical and with a constant flow) taking care that no water is spilled into the funnel.
3. Turn the stool with gauge around with a speed of 8 turns per minute during 5 minutes.
4. Turn off the shower after these 5 minutes and measure the amount of water in the reservoir with the measuring glass.
5. Calculate the leakiness in mm/min.

Turning around the gauge is needed because the leakiness is unevenly distributed along the circumference of the gauge (see also Section 3) and in the field the gauge does not have a fixed orientation with respect to the North.

Zero leakiness in the on-site test (funnel turned upside-down) always corresponded with zero leakiness in the shower test. On the other hand, leakiness in the on-site test did not always imply leakiness in the shower test. As shown in Figure 2, there is no clear relationship between the

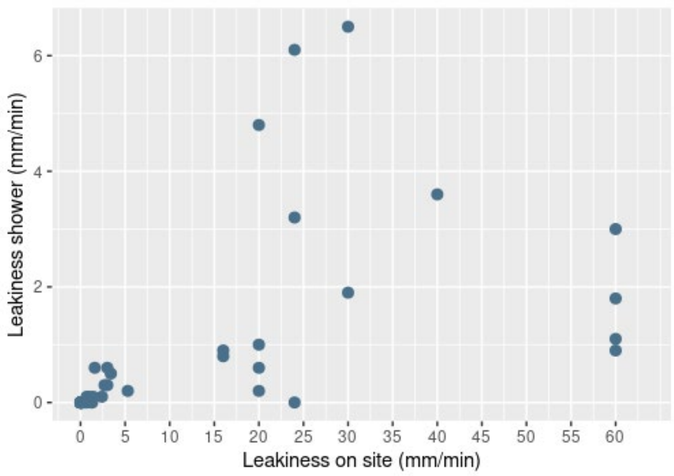

Figure 2: Comparison of the leakiness obtained in the on-site test in June-July 2017 and the shower test at KNMI. Details of the results are given in Appendix A.

leakiness in the on-site test and the shower test. For gauges with small on-site leakiness values, no leakiness was found in the shower test. In one case, even an on-site leakiness of 24 mm/min did not result in leakiness in the shower test.

[5] It was not feasible to test all gauges at KNMI because of a lack of repaired and sealed spare gauges. This was also not found necessary because about 100 of the new gauges had already been replaced in the past. The leakiness of those defect new gauges cannot be tested anymore and can only be assessed in a comparison with surrounding stations with non-leaky gauges (see Chapter 3).

Based on the results of the shower test, it was considered admissible to accept rain gauges with small leakiness values in the on-site test (< 1.0 mm/min) as non-leaky. This enlarges the number of non-leaky gauges that potentially might be used as a reference. For a reference station it is, however, also necessary that the new gauge was not replaced earlier.

2.3. Study of metadata

Here two types of metadata are distinguished, type I and type II. Type I is the regular metadata needed to identify data. For instance, name and position of a station, measuring period, variables measured. In addition, type II metadata is needed to assess the quality of the data. For instance, information on changes in gauge type (including the measuring height), relocations of the gauge, and changes in measurement method and environment of the gauge.

The gauge history at each station (type II metadata) is found in inspection reports. Each MN station is inspected on average once in two years by a KNMI station inspector. In special situations (e.g., when something is wrong with a rain gauge) a station may be visited more than once in two years. Inspection reports are stored in a database. These reports were studied here to reveal the following information: (a) date of placement of the new gauge in the 2012-2014 period, and (b) date(s) of replacement of a defect rain gauge. Stations not leaky according to the on-site test in June-July 2017, would e.g. be classified as potentially leaky when the metadata revealed a replacement of a defect new gauge before the date of the on-site test. In that case leakiness cannot be estimated with a leakiness test because the gauges were sent back to the manufacturer for repair.

The metadata revealed that between placing the new gauges in the 2012-2014 period and the on-site leakiness test in June-July 2017, about 100 gauges had become defect and were replaced (mostly by a repaired version of a new gauge and sometimes by an old type gauge). Independent of the results of the on-site leakiness test and the shower test, these stations were classified as potentially leaky. In the end, 131 stations could be classified as non-leaky[6] for the whole period between the placement of the new gauge and the leakiness test in June-July 2017. These were used as reference for correcting the rainfall data from stations with potentially leaky gauges. Figure 3 shows the locations of the stations used as reference and the stations with potentially leaky rain gauges.

[6] Consisting of all stations with (a) rain gauges with leakiness values in the on-site test < 1.0 mm/min (including the old type gauges), and (b) no replacement of a defect rain gauge by a repaired one between the first placement of the new gauge in the 2012-2014 period and the on-site test in July 2017.

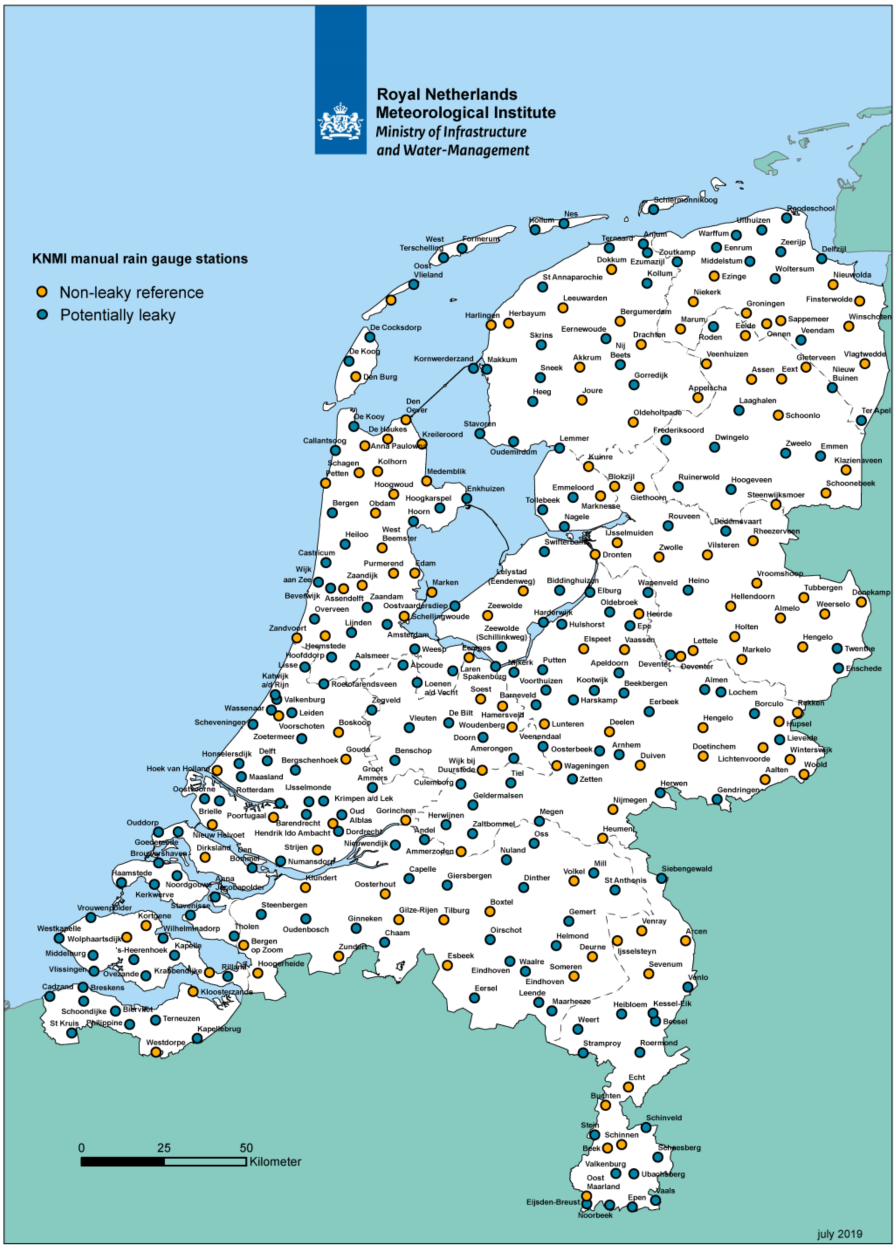

Figure 3: Map of the 131 non-leaky reference stations (yellow) and the 320- 131 = 189 stations with potentially leaky gauges (blue) in the manual daily rainfall network (MN).

2.4. Field experiment at the KNMI test site

In addition to the experiments described above and the study of metadata, a field experiment at the KNMI test site in De Bilt was set up to investigate the differences in rainfall between the gauges in more detail. The purpose of the experiment was to increase our understanding of the effect of leakiness and to value the statistical corrections. Eleven manual rain gauges were compared. The results are described in Appendix B. A large day-to-day variance of the effect of leakiness was found, related to the weather conditions and the placement of the funnel on the reservoir which varies from day to day. This implies that at best statistical corrections are possible, because information on exact weather conditions and the placement of the funnel on the reservoir are virtually unknown for the manual rain gauges.

The field experiment further shows that the effect of leakiness is generally larger in winter than in summer. This can be attributed to the higher wind speeds and lower rainfall intensities (smaller drop sizes) in winter, resulting in a larger angle of inclination of the rainfall. The most leaky gauge in the field received up to 40% more rainfall (for some winter months) than the non-leaky gauges.

Photo 4: Experiment at the KNMI test site in De Bilt comparing 11 manual rain gauges, performed in the period June 2017 – May 2018. Among the gauges are two old type gauges, four new type gauges, two new type gauges repaired with spot welding, two new type gauges with shifted rings, and a sealed new type gauge (lower left).

3. Description of the correction method

The correction method presented in this chapter is statistical. This is common practice in climatology but also inevitable here for three reasons. First, the development of leakiness in time is unknown. Second, gaps are irregularly distributed along the funnel circumference, and therefore the leakiness of a gauge depends on the part of the funnel facing the wind and rain. However, the placement of the funnel on the reservoir with respect to the North varies from day to day and is unknown. Third, local weather other than the amount of rain is not reported at the MN stations. Factors influencing leakiness, like wind speed and rainfall intensity, are only available from the AWS network. Especially for wind speed this may be problematic as it generally requires a transformation of a measured wind speed over rather open terrain to a wind speed at a more sheltered location.

The core of the correction method is a statistical comparison of the 2-monthly rainfall amounts at a station with a (potentially) leaky gauge with the mean 2-monthly rainfall at a set of neighbouring stations with non-leaky gauges. The latter serves as the reference. In the previous chapter, we divided the MN stations into stations with non-leaky gauges and stations with (potentially) leaky gauges. The MN stations with (potentially) leaky gauges are candidate stations for correction, the other stations are used as reference stations. The comparison between the rainfall at a candidate station and the reference starts well before the introduction of the new gauge. The period up to the placement of the new gauge is the baseline period. Statistically significant differences with respect to the baseline period are examined further to determine the need for correction. Statistical models are fitted to the percentage differences in 2-monthly rainfall at the candidate station and the reference to describe the seasonal variation in these differences and the systematic changes resulting from gauge leakiness. The model that best describes these effects is used to derive correction factors for the rainfall data from the candidate station.

In this chapter, we first describe the data used in the analysis. Thereafter, all steps in the correction process are discussed in detail using an example. The uncertainty of the correction is addressed at the end of this chapter.

3.1. Data

Three KNMI data sources are used for the correction of the data from the stations with leaky rain gauges: (1) daily rainfall data from the MN, (2) hourly rainfall and wind data from the automatic weather station (AWS) network, and (3) metadata of the individual stations in the MN.

Daily rainfall data from the manual daily rainfall network (MN)
Daily rainfall data from the MN is used for the period 1 January 2001 - 30 June 2018. Since 1946 the network has an almost constant density with an average distance between stations of about 10 km. Currently there are about 320 rain gauges (see Figure 3 for locations). The gauges are mostly located in sheltered environments (gardens of houses, near farms, etc.). The rain gauges are operated by voluntary observers. Each morning the 24 h

(8:00–8:00 UTC) amount of rainfall is measured and since 1995 digitally transferred to KNMI by telephone.

The daily rainfall measurements are subjected to extensive quality control[7]. Suspect values are traced by comparing the daily measurements with those from neighbouring stations and could often be recovered after consulting the observer. Incidentally, multi-day rainfall amounts are measured (e.g., due to absence of the observer). These are distributed across individual days using measurements at neighbouring stations and, more recently, radar rainfall. After the quality control, the data are made publicly available via the KNMI website. For more details see Brandsma (2014).

A rain gauge generally catches less rain than the actual rainfall. A major cause of this undercatch is the so-called wind error. A rain gauge disturbs the air flow causing extra turbulence. Because of this part of the rain is blown over the gauge. The magnitude of the wind error strongly depends on the local environment. On average this is about 3% in the Netherlands but it can be up to about 10% for open areas (Buishand and Velds, 1980). Station relocations and changes in the environment of the gauge can therefore lead to serious inhomogeneities in the rainfall data. Corrections for these inhomogeneities are outside the scope of the present study.

Hourly rainfall and wind data from the automatic weather station (AWS) network

Hourly rainfall data from the automatic weather station network is used for the period 1 January 2001 - 30 June 2018. For each AWS, the following daily weather variable is calculated:

$$FH_{\mathrm{wet}}/{I_{\mathrm{wet}}}^{0.8},$$

where FH_{wet} is the mean wind speed (m/s) on wet hours and I_{wet} the mean rainfall intensity (mm/h) on wet hours. The field experiment at the KNMI test site shows a positive relationship between leakiness and this weather variable. See Appendix B.

Automatic rain gauges are installed at 32 of the 35 AWS locations in the Netherlands (see Figure 4 for locations). They are mostly situated in rural open areas. Rainfall is measured using the so-called KNMI rain gauge (see e.g., Wauben, 2004, for a detailed description). This electric gauge is of the floating type and measures rainfall with a time resolution of 12 seconds. The funnel and reservoir are heated if the air temperature falls below 4°C in order to melt solid precipitation. The gauge has a calibration interval of 14 months. Currently, precipitation values are in situ aggregated to 1-min, 10-min and 1-hour totals and subsequently archived at the KNMI headquarters in De Bilt. Only the hourly data is validated by the validation division and is used in this research. The validated hourly data is publicly available via the KNMI website.

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[7] So far, no monitoring of long-term differences between a station and its neighbouring stations takes place. In retrospect, this could have revealed the problem with leaky rain gauges earlier.

Before 2001 the majority of the automatic rain gauges was placed in a so-called English setup. Since 2001 this setup has slowly been abandoned and today almost half of the rain gauges are placed in an Ott windscreen. This affects the wind error of the gauges and introduces an inhomogeneity. For further details, see Brandsma (2014).

Wind speed and direction at an AWS location are generally measured at a height of 10 m with a cup anemometer and a wind vane.

Type II metadata of the individual stations in the manual network
For each candidate station, type II metadata is needed for the correction procedure. These data are not publicly available. From the inspection reports the following metadata are extracted for each candidate station (from 2001 onwards):

1. Dates of relocations (if any).
2. Date of placement of the new gauge in the 2012 - 2014 period.
3. Date(s) of replacement of a defect gauge (if any).
4. Date and result of the on-site leakage test in June - July 2017.

3.2. Methodology

For the correction of the rainfall data from potentially leaky stations we use the non-leaky stations as a reference. The use of other references, like the

Figure 4: Positions of the 35 automatic weather stations. The three stations with names and numbers in blue have no rain gauge.

rainfall from the automatic weather stations (AWS) or radar rainfall, is not viable. The density of the AWS network is too low and the electric rain gauges in this network generally show a larger undercatch than the manual gauges (Brandsma, 2014). The current radar rainfall estimates are only useable for this purpose when corrected with the spatially high-resolution rainfall of the MN. Therefore, radar rainfall is not an independent source of data to be used for comparison or correction.

In the beginning of this chapter we explained the principle of the correction method. The method is now described in more detail using the process steps in the diagram in Figure 5. These steps are discussed below, using the data from the potentially leaky station of Lemmer (gemaal[8] Buma)[9] as an illustration. The whole process is semi-automatic where for each candidate station the calculations and production of figures are performed automatically[10]. Only at certain points expert opinion determines how to proceed (for instance, when it is unclear whether an inhomogeneity results from a leaky gauge or a gauge relocation). All calculations were done in R (R Core Team, 2019).

[8] 'Gemaal' is the Dutch word for pumping station.
[9] With hindsight, Lemmer turned out the station with the largest maximum leakiness.
[10] For all stations the results as for Lemmer are stored in html files. These are archived together with the corrected series in the KNMI climatological database.

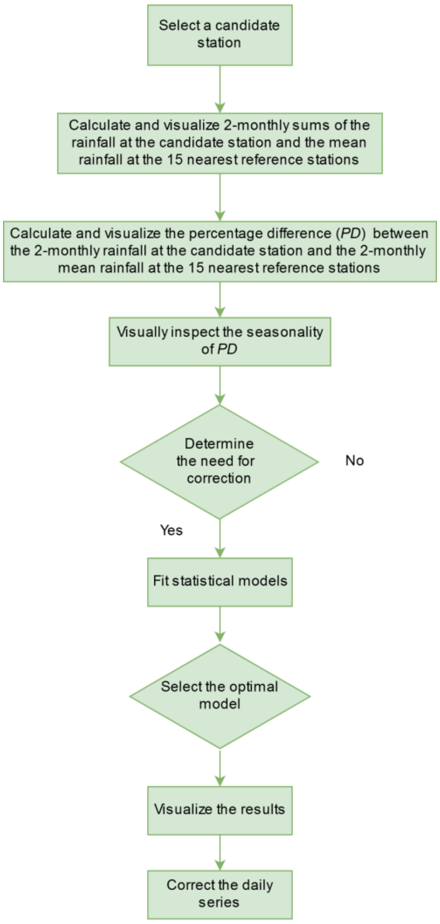

Figure 5: Steps in the correction process for a single candidate station.

Select a candidate station

The example of Lemmer shows the station name and number, the break dates, relocation dates, result of the leakiness test and notes. Break dates are defined as dates where abrupt changes in leakiness may occur. Here they represent, respectively, the date of placement of the new gauge, the date a repaired gauge was placed and the date of the combined on-site leakiness test and sealing of the gauge. Most stations have two or three of these break dates (deviations are mentioned under 'notes'). Lemmer is one of the 100 stations where a new rain gauge was replaced by a repaired (spot welded) one because of a loose funnel ring. In the case of Lemmer, there are no station relocations since January 2001. The leakiness test refers to the on-site leakiness test and yielded a value of 55.8 mm/hour. No special notes were found in the metadata.

Calculate and visualize 2-monthly rainfall sums for the candidate and the reference

For the period January 2001 – June 2018 2-monthly rainfall sums (JF, MA, MJ, JA, SO, ND) are calculated. The period from January 2001 to the date of the placement of the new gauge at candidate stations serves as the baseline period. This period is long enough to get a reliable estimate of the difference in mean rainfall at the candidate station and the reference stations under non-leaky conditions[11]. The period after June-July 2017 is not used in the calculation of the correction but is used for visual inspection of the effect of the correction and the sealing of the gauges in the June-July 2017 period.

Two-monthly rainfall sums are used because a 2-month interval is short enough to allow for seasonable dependence of the corrections and large enough to prevent unrealistic percentage differences between the candidate station and the reference[12]. For 2-monthly periods with a breakpoint in it (e.g., the date of placement of the new gauge or the date of the sealing of the gauge), the data before and after the break is allocated to the current, previous or next 2-month interval, depending on the position of the break. For instance, when a break occurs on 17 January, the data until 17 January is included in the ND interval of the previous year and the period from 17 January till the end of February constitutes the JF interval for that year.

The reference series is based on the 2-monthly rainfall sums from a set of neighbouring non-leaky stations rather than the 2-monthly rainfall sums at the closest (non-leaky) station only to reduce the effect of possible inhomogeneities in the reference data. This is common practise in detecting inhomogeneities in climate data (Buishand, 1982; Alexandersson, 1986). Here the 15 nearest (non-leaky) stations are considered. These stations are found by calculating and sorting the distances between the candidate station and all non-leaky stations. The number of 15 stations was found to be a good compromise between (a) having enough stations for getting an almost homogeneous reference series, and (b) having no influence of rainfall from far-away stations which is less correlated with the rainfall at the candidate station. The 2-monthly rainfall sums of the reference stations are averaged to obtain the 2-monthly reference rainfall.

Figure 6 shows the 2-monthly rainfall sums for Lemmer and the reference series used for this station. There is a strong resemblance between the two series. Two relatively large 2-monthly sums around 2014 in the Lemmer

Metadata

Variable	**Value**
Station name	Lemmer (Gemaal Buma)
Station number	359
Break dates (yyyymmdd)	20130313, 20150215, 20170616
Relocation dates (yyyymmdd)	NA
Leakness test (mm/min)	55.8
notes	NULL

Metadata for Lemmer. For description see the text.

series are, however, not found in the reference series.

[11] In the case of a relocation of the rain gauge at the candidate station, the data before the relocation are sometimes omitted yielding a shortened baseline period.
[12] We calculate percentage differences between the rainfall at the candidate station and the mean rainfall at the reference stations. Using monthly sums then incidentally results in unexpected percentage differences when the reference rainfall becomes close to zero. The residuals in statistical models for the percentage differences are then no longer normally distributed. For the 2-monthly percentage differences the residuals turn out to be almost normally distributed.

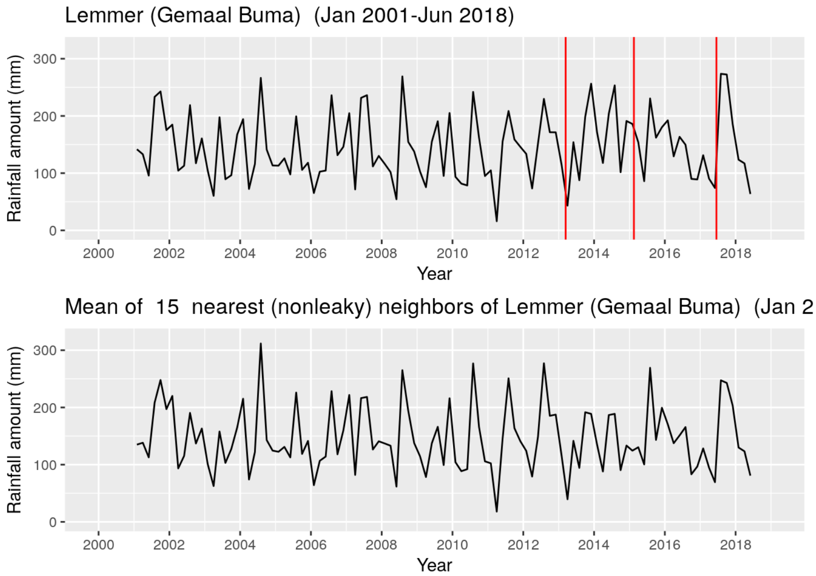

Figure 6: Two-monthly rainfall amounts of Lemmer and the mean of the 15 nearest (non-leaky) reference stations. The red vertical lines represent the break dates: 13 March 2013 the new gauge was placed, 15 February 2015 the gauge was replaced by a repaired one, and 16 June 2017 the leakiness test was performed and the gauge was sealed.

Calculate and visualize the percentage difference (*PD*) in 2-monthly rainfall at the candidate station and the nearest reference stations

The percentage difference (*PD*) in 2-monthly rainfall at the candidate station and the reference is calculated as:

$$PD = 100\,\frac{P_{\text{cs}} - P_{\text{ref}}}{P_{\text{ref}}},$$

where P_{cs} and P_{ref} are the 2-monthly rainfall sums for the candidate station and the reference series, respectively.

A visual inspection of the *PD* is the first step in the analysis. This gives a first impression of the severity of any potential leakiness of the gauge at the candidate station and its development over time. For Lemmer the figure of *PD* (Figure 7) clearly illustrates the different aspects when dealing with a leaky rain gauge. Four intervals (Int1-Int4) are distinguished in the figure. Int1 is the baseline period (with no leakage). After the placement of the new gauge, the gauge became leaky and received too much rainfall (Int2). The leakage seems to increase with time. After the placement of the repaired new gauge, the gauge still seems leaky but less than before and no trend is apparent (Int3). In the baseline period (Int1), the rainfall of Lemmer is about 5% smaller than the reference. This is an indication that the rain gauge in Lemmer is situated at a windier location than, on average, the reference stations. The windier a location, the larger the wind error. Lemmer is situated on the shore of Lake IJssel and is known as a windy location.

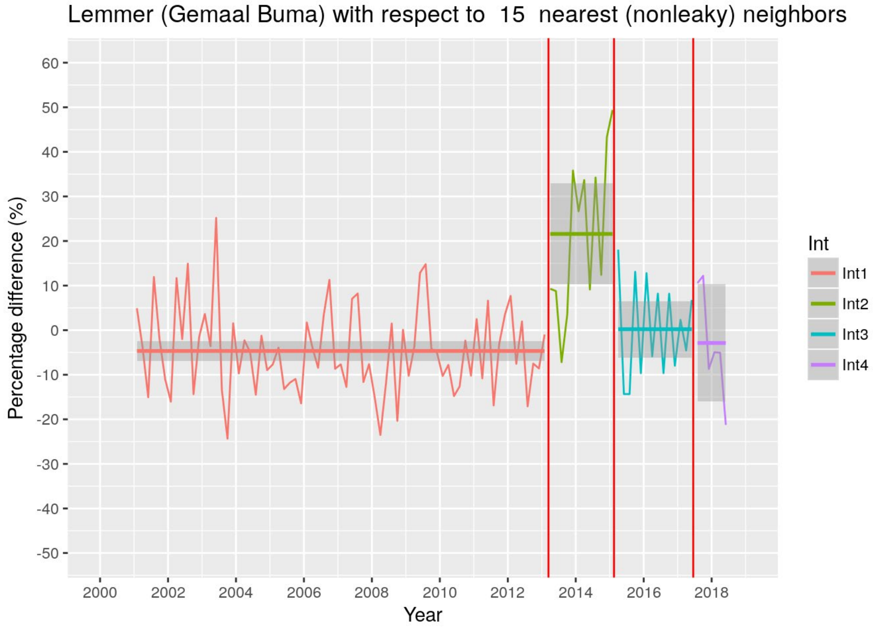

Figure 7: Percentage difference (PD) for Lemmer. Four intervals are defined: Int1 = the baseline period, Int2 = the period where the first new gauge was active, Int3 = the period where the second, repaired, new gauge was active, and Int4 = the period after sealing the gauge. The horizontal lines in each interval represent the mean PD with the 2x standard error band (dark grey).

Visually inspect the seasonality of *PD*

For each of the four intervals the mean *PD* is calculated for the six 2-monthly periods January-February (JF), …, November - December (ND) of the year. This may give an indication of whether or not seasonality needs to be included in the correction model. For Lemmer Figure 8 shows for the short periods Int3 and Int4 an irregular behaviour. For Int2 there is, however, a clear indication of a seasonal effect, with leakiness being larger in winter than in summer. This could be expected as wind speed in winter is higher and rainfall intensities are lower than in summer. This results in more

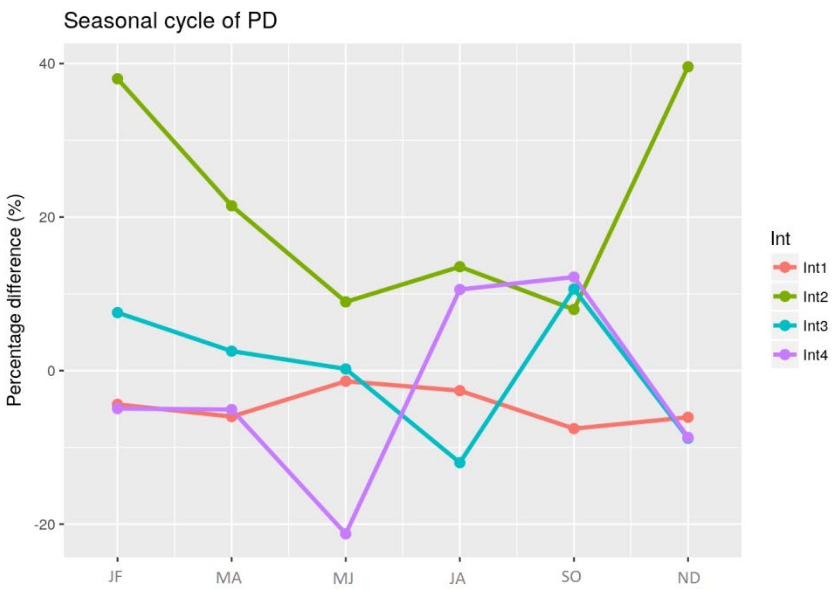

Figure 8: Seasonal cycle of PD for Lemmer for each interval.

rainfall splashing against the outer side of the funnel and thus more water leaking into the reservoir. This is further enhanced by rainfall duration being longer in winter than in summer.

For the first, or baseline period (Int1) − without leaky rain gauges − there is also a weak indication of seasonality. Here the effect for Lemmer is opposite to the situation of a leaky rain gauge. From May to August the mean *PD* is close to zero whereas in the remainder of the year the mean *PD* is negative. Lemmer is a relatively windy location compared to the reference stations resulting in larger wind errors in the winter half-year than the summer half-year. For other candidate stations this may be different depending on how windy/sheltered the location is with respect to the reference.

Determine the need for correction

To determine the need for correction we used the following approach:

1. A one-way ANalysis Of VAriance (ANOVA) is performed to determine the statistical significance of the differences in the mean of the *PD*s in the intervals between breakpoints using an *F*-test. The interval after the date of the on-site leakiness test and sealing of the gauge is not considered in the ANOVA. Mostly a one-sided *t*-test for each individual interval is also done to determine if *PD* is significantly larger than *PD* in the baseline period. The test is one-sided because it is expected that leakiness increases *PD*. Both for the *t*- and *F*-tests, the 0.05 level is chosen to determine whether the result is significant or not.
2. Rainfall series with statistically significant changes that could be attributed to gauge leakiness needed correction. In a number of cases it was not clear whether a significant change was due to gauge leakiness, e.g., when the period of a leaky rain gauge more or less coincided with a gauge relocation. Expert judgement was then needed to decide whether the rainfall data had to be corrected or not. If not, then the station was classified as 'potentially leaky, no correction applied', just like the stations with non-significant changes.

As could be expected, for Lemmer the ANOVA shows strong evidence of changes in the mean of the *PD*s. The *result* of the *F*-test for equality of means is very significant (*p*-value is 1.52e-10).

The individual *t*-test shows that the mean *PD* of 21.59% in Int2 is significantly larger than the mean *PD* of -4.67% in the baseline period Int1 (*p*-value is 2.27e-11). For the third period (Int3) the mean *PD* equals 0.22%, which also differs significantly from the mean *PD* in the baseline period (*p*-value is 0.04745). We conclude the gauge is leaky in both periods Int2 and Int3 and that the rainfall data for these periods need correction.

Fit statistical models

The example of Lemmer shows that several features have to be taken into account when modelling *PD*. For instance, in the second period (Int2) there is an increase of leakiness with time, while in the third period (Int3) the leakiness looks more or less constant with time. Further, in the second period (Int2) seasonality of the effect of leakiness might be important (see Figure 8). Seasonality in the reference series may also play a role globally over the whole length of the series, as revealed by the baseline period (Int1).

Based on the example of Lemmer and other candidate stations, we formulated the following starting points for the formulation of statistical models for *PD*:

1. There is a possibility of a gradual increase of *PD* with time, because of a leaky gauge.
2. The change in *PD* may exhibit a seasonal pattern.
3. In the case that a defect new rain gauge was replaced by a repaired one – using spot welding – the change in *PD* is assumed to be constant (as in Int3 for Lemmer).
4. The *PD* of a gauge may exhibit a seasonal variation in the baseline (i.e. non-leaky) period. This seasonality depends on whether the candidate station is located in a relatively open or sheltered environment or in an area with relatively strong or weak wind speed. Any seasonal variation of the change in *PD* during a leaky period, is superimposed on the seasonal variation in the baseline period.

Depending on the situation, the following types of models for *PD* are considered (in all cases the period after the sealing of the gauge, int4 in the case of Lemmer, is excluded):

1. A base model with constant mean *PD* in the intervals between break dates (horizontal lines as in Figure 7 of the *PD* time series of Lemmer).
2. A model with a constant change in *PD* in certain intervals and a linearly increasing trend in *PD* in other intervals.
3. Three models with a constant change in *PD* in certain intervals and a seasonally varying change in *PD* combined with an increasing trend in other intervals.

For all models a 'global seasonal term' is added to take into account a possible seasonal variation in *PD* during the baseline period (and assuming this variation continues after the baseline period, i.e. into the leaky periods). The seasonal term in the type 3 models consists of a cosine (with a peak in January/February and a trough in July/August) or the weather variable $FH_{wet}/I_{wet}^{0.8}$ derived from the nearest AWS.

The five different models were fitted by ordinary least squares. For Lemmer this takes the following form (in R-notation):

```
Model_1 <- lm(PD ~ -1 + cos_glob + sin_glob + Int, data = x)

Model_2 <- lm(PD ~ cos_glob + sin_glob + trend2 + intercept3,
              data = x)

Model_3 <- lm(PD ~ cos_glob + sin_glob +
              I(trend2*FHwet/Iwet^0.8) + intercept3, data =
              x)

Model_4 <- lm(PD ~ cos_glob + sin_glob + trend2 +
              I(trend2*cosine2) + intercept3, data = x)

Model_5 <- lm(PD ~ cos_glob + sin_glob + trend2 + cosine2 +
              intercept3, data = x)
```

The following comments apply to these models:

- The model formula is given within the brackets before the comma. The dependent variable *PD* stands on the left of ~ and the explanatory variables are given on the right of ~. 'lm' means linear model.
- Data = x concerns the 2-monthly variables (the dependent and explanatory variables) in the *PD* formulas and cos_glob and sin_glob constitute the global seasonal term.
- In Model 1, the -1 indicates the exclusion of a global intercept and Int represents the intercepts in Int1, Int2 and Int3 (dummy variables with the value 1 in the specific interval and zero elsewhere).
- In Model 2, trend2 represents a linearly increasing trend in Int2 and equals zero elsewhere. Intercept3 is a dummy variable with the value 1 in Int3 and zero elsewhere.
- In Model 3, I(trend2*FHwet/Iwet^0.8) is a combination of the seasonally varying weather variable and the trend2 variable (thus zero outside Int2).
- I() is an identity function. It is used in R to treat the part between the brackets as a single predictor.
- In Models 4 and 5 the cosine2 variable has the peak in January/February and the trough in JA (July/August)[13].
- The only difference between Models 4 and 5 is that in Model 5 the cosine2 variable and trend2 variable are separate variables while in Model 4 the cosine2 variable is replaced by a (new) variable which is the product of cosine2 and trend2.

Select the optimal model

The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are used for the final model selection. Apart from the residual variance as a measure of goodness of fit, AIC and BIC contain a penalty term for model complexity. In AIC the penalty is $2k$, whereas in BIC the penalty is $\ln(n)\,k$, with n the number of data points and k the number of parameters to be estimated. For $n > 7$, BIC thus penalizes model complexity heavier than AIC. The model with the lowest AIC or BIC is selected. When AIC and BIC do not point to the same *PD* model, the model with the lowest BIC is used.

For Lemmer the results are as follows:

[13] This is done because of physical considerations. As noted in Appendix B, the amount of water splashing against the sides of the funnel is proportional to $FH_{wet}/I_{wet}^{0.8}$, which has its peak in winter and its trough in summer.

	AIC	BIC
Model 1	765.3	780.9
Model 2	750.4	766.0
Model 3	749.0	764.6
Model 4	746.9	765.1
Model 5	744.5	762.7

Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) for Lemmer. Model 5 has the lowest value for both AIC and BIC.

In this case, both AIC and BIC point to Model 5 and thus this model is selected.

Visualize the results

Figure 9 compares the results of all models visually. Model 1 gives an incomplete description of the leakiness effect, resulting in a poor reproduction of the actual PD time series during Int2. Model 2 is a large improvement but is still inferior to Models 3 to 5, i.e. the models with the trend and seasonal term. The differences between the Models 3 to 5 are relatively small, but also ‘on-the-eye’ Model 5 performs best.

Figure 9 also shows that the global seasonal term is small. The amplitude of this term is 1.6% and is not significant at the 5% level. For a number of stations a significant amplitude of about 5% was found.

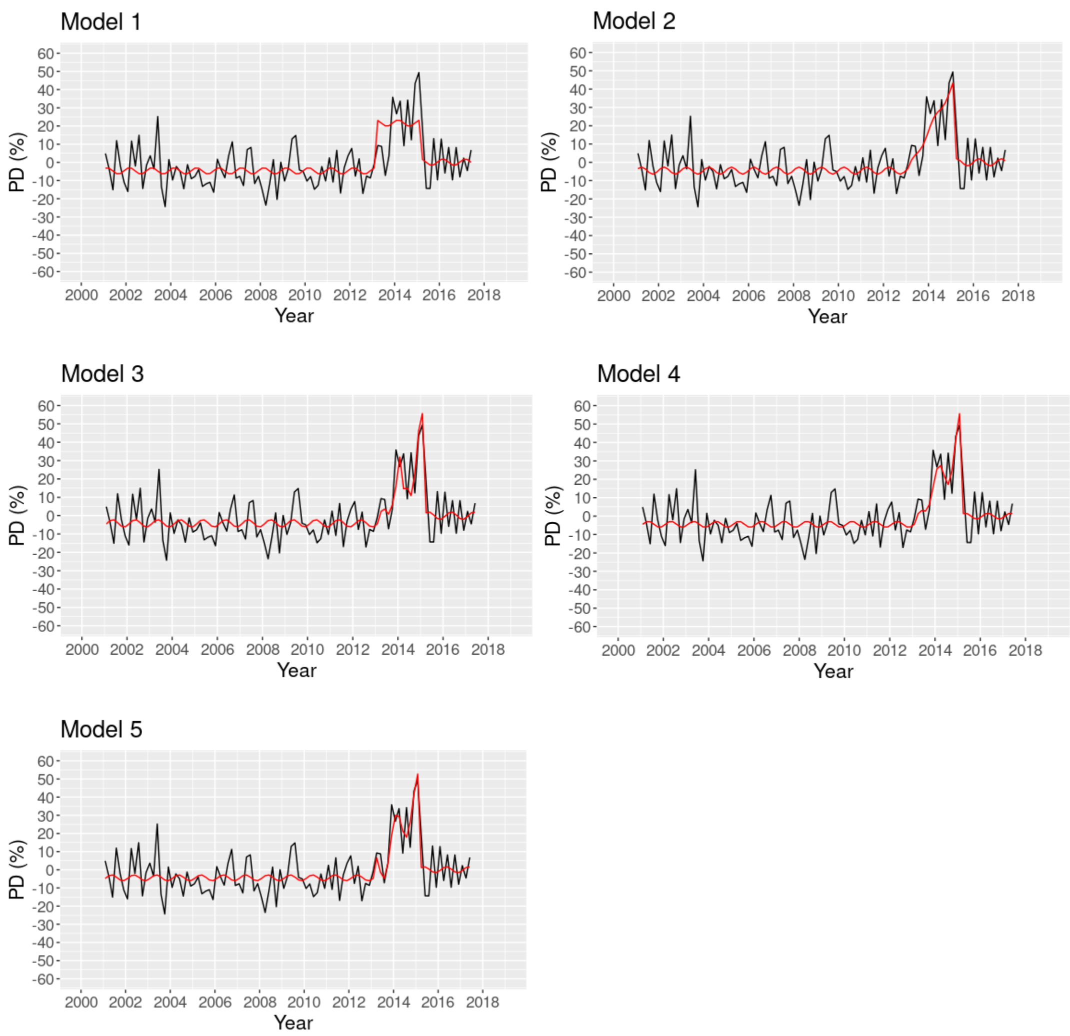

Figure 9: PD (black line) and modelled PD (red line) for all five models for Lemmer. Model 5 is the selected model.

Correction of the daily series

Using the model results for *PD*, the correction factor *CF* is calculated as:

$$CF = \frac{PD_1/100 + 1}{PD_2/100 + 1},$$

where PD_2 is the modelled percentage difference and PD_1 the percentage difference that would have been obtained if the gauge was not leaky. The global seasonal term in the expressions for PD_1 and PD_2 was omitted here, because its effect on *CF* turned out to be small (no more than ≈ 0.01 for candidate stations with a large amplitude of this term). The right-hand side may incidentally become larger than 1, *CF* is then set equal to 1. Figure 10 shows the 2-monthly values of *CF* for Lemmer.

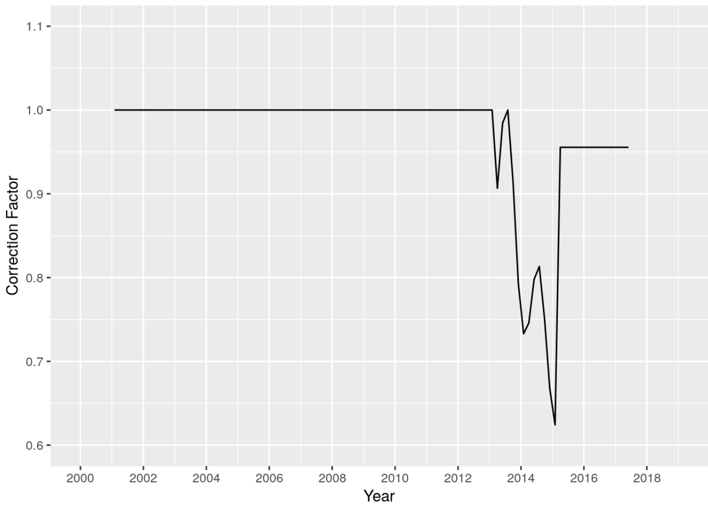

Figure 10: The correction factor CF for Lemmer.

The 2-monthly correction factor *CF* is subsequently used to correct the daily series, taking into account the dates of the breakpoints. The corrected daily amounts were rounded to tenths of a millimetre. We used the rounding procedure proposed in Buishand (1988), to ensure that the monthly sums correspond with the monthly sums of the non-rounded corrected daily amounts.

```
## # A tibble: 10 x 6
##    statno               statna  year month   day     cf
##     <dbl>                <chr> <int> <int> <int>  <dbl>
##  1    359 Lemmer (Gemaal Buma)  2013     3    13 0.9066
##  2    359 Lemmer (Gemaal Buma)  2013     3    14 0.9066
##  3    359 Lemmer (Gemaal Buma)  2013     3    15 0.9066
##  4    359 Lemmer (Gemaal Buma)  2013     3    16 0.9066
##  5    359 Lemmer (Gemaal Buma)  2013     3    17 0.9066
##  6    359 Lemmer (Gemaal Buma)  2013     3    18 0.9066
##  7    359 Lemmer (Gemaal Buma)  2013     3    19 0.9066
##  8    359 Lemmer (Gemaal Buma)  2013     3    20 0.9066
##  9    359 Lemmer (Gemaal Buma)  2013     3    21 0.9066
## 10    359 Lemmer (Gemaal Buma)  2013     3    22 0.9066
```

Daily correction factors for the first 10 days of the leaky period in Lemmer.

3.3. Uncertainty of the correction factor

Confidence intervals for the correction factor can be obtained using a bootstrap procedure. This is done as follows:

1. Calculate the residuals as the differences between the observed percentage differences *PD* and the fitted values from the model.
2. Create 1000 bootstrap samples by resampling the residuals with replacement (Efron and Tibshirani, 1993).
3. For each bootstrap sample calculate percentage differences PD^* for each 2-monthly period as the sum of the fitted value from the model and the resampled residual for that period.
4. Fit the model to these PD^* values, yielding new regression coefficients.
5. Use the new regression coefficients to calculate CF^*.
6. Calculate for each 2-monthly period the quantiles of the 1000 CF^* values to obtain the desired confidence interval.

Figure 11 shows a 90% bootstrap confidence band for the correction factor of Lemmer. In Int3, with a relatively small leakage effect (≈ 5%), the upper confidence limit (0.95 quantile) equals 1.0[14]. The confidence band is rather wide owing to the large variability of the 2-monthly PD values and the short length of the leaky period.

For the other stations, similar figures can be made.

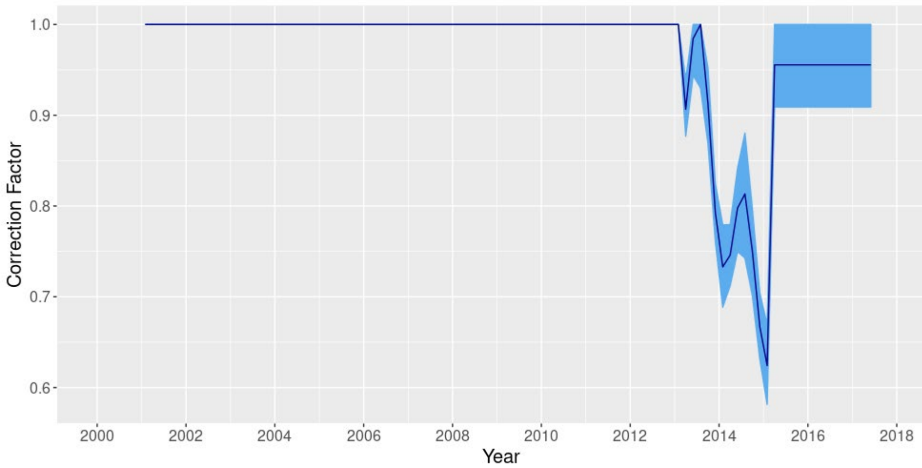

Figure 11: 90% bootstrap confidence band for the correction factor of Lemmer.

[14] The number of bootstrap samples for which *CF* = 1 in Int3 equals 61. This bootstrap result is not significant at the 5% level. This is in contrast with the result of the *t*-test, which was just significant at the 5% level. The latter is leading for the decision to correct or not.

4. Results

We compared the rainfall series of all stations with potentially leaky rain gauges with a reference series. Each references series consisted of the mean rainfall of the 15 nearest non-leaky stations. For 65 of the 320 stations (operational during 2012-2017) a correction was applied to the data for (part of) the 2012-2017 period. These stations measured too much rainfall because water splashing against the sides of the funnel entered into the reservoir. The daily time series of the 65 stations were corrected. Since the publication of this report, the corrected series replace the original series in the KNMI climatological database and the derived operational products were adapted as well. Figure 12 shows the locations of the 65 stations with

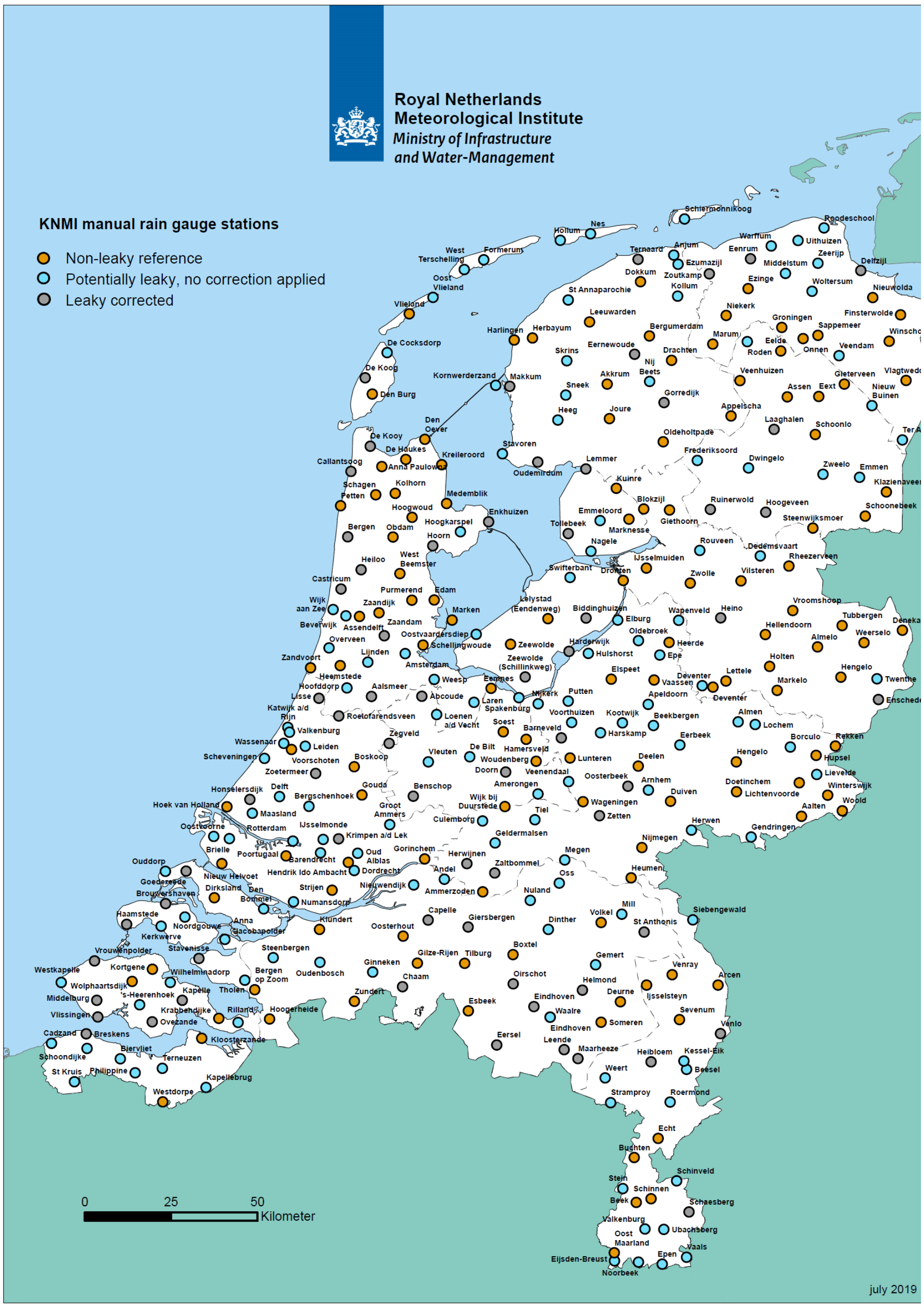

Figure 12: Map of non-leaky reference stations (yellow), potentially leaky stations, no correction applied (light blue), and leaky stations with corrected data(grey).

corrected series together with the locations of the reference stations and the potentially leaky stations where no correction was applied.

For each of the 65 corrected series Table 1 shows information on the period to which the correction applies, the magnitude of the correction factor and the correction model applied. Correction factors are always < 1 because leakiness always results in measuring too much rainfall.

Table 1: Summary of the results for the 65 corrected rainfall series. The begin and end date refer to the period where the data were corrected. For the correction factor the smallest (min) and mean value (mean) in the correction period are given. In the case of a constant correction min and mean are equal. The correction model refers to one of the five models presented in the previous chapter. Note that the smallest correction factor gives the largest correction.

No	Name	Correction period (yyyymmdd)		Correction factor		Correction model
		begin	end	min	mean	
458	Aalsmeer	20121121	20170622	0.897	0.914	1
572	Abcoude	20170222	20170613	0.794	0.794	1
580	Barneveld	20130828	20150311	0.718	0.868	3
561	Benschop	20130206	20150224	0.700	0.855	3
234	Bergen (NH)	20120516	20170602	0.858	0.858	1
366	Biddinghuizen	20131016	20170615	0.937	0.937	1
705	Breskens	20130815	20150827	0.874	0.874	1
736	Brouwershaven	20150701	20170612	0.925	0.925	1
21	Callantsoog	20120510	20170628	0.878	0.937	2
844	Capelle (NB)	20140313	20170718	0.912	0.912	1
235	Castricum	20121121	20140722	0.788	0.893	3
834	Chaam	20130807	20170703	0.847	0.909	1
22	De Koog	20130626	20170712	0.746	0.912	3
25	De Kooy	20120510	20150929	0.947	0.947	1
141	Delfzijl	20121129	20170621	0.947	0.947	1
509	Doorn	20161124	20170624	0.877	0.877	1
154	Eenrum	20131127	20170620	0.938	0.938	1
90	Eernewoude	20120810	20170627	0.957	0.957	1
915	Eersel	20160527	20170703	0.868	0.868	1
919	Eindhoven (VB)	20140410	20160526	0.919	0.919	1
221	Enkhuizen	20120703	20170615	0.906	0.952	2
665	Enschede	20140530	20160301	0.889	0.889	1
892	Giersbergen	20140314	20170706	0.831	0.915	3
446	Goedereede	20130613	20170624	0.892	0.892	1
82	Gorredijk	20131024	20170705	0.932	0.932	1
752	Haamstede	20131126	20170612	0.878	0.933	2
516	Harderwijk	20131101	20170420	0.768	0.880	5
967	Heibloem (L)	20131121	20151125	0.880	0.880	1
217	Heiloo	20120516	20170628	0.936	0.936	1
340	Heino	20130320	20150408	0.809	0.885	2
896	Helmond	20140411	20160525	0.750	0.875	3
830	Herwijnen	20121130	20161129	0.853	0.914	2
480	Honselersdijk	20121012	20150303	0.706	0.901	4
332	Hoogeveen	20131120	20170704	0.945	0.945	1
222	Hoorn (NH)	20130130	20170314	0.717	0.866	3
735	Kapelle	20130808	20170614	0.931	0.931	1
483	Krimpen aan de Lek	20130705	20160926	0.856	0.929	3
323	Laaghalen	20131128	20170620	0.901	0.934	2
912	Leende	20160526	20170706	0.903	0.903	1
359	Lemmer (Gemaal Buma)	20130313	20170615	0.624	0.872	5
454	Lisse	20150121	20170704	0.843	0.920	3
918	Maarheeze	20140411	20170706	0.863	0.949	3

65	Makkum	20121115	20161215	0.826	0.899	2
756	Middelburg	20130116	20150811	0.814	0.814	1
906	Oirschot	20140314	20160525	0.832	0.899	2
578	Oosterbeek	20130207	20150312	0.845	0.903	2
70	Oudemirdum	20150214	20170706	0.933	0.933	1
754	Ovezande	20130719	20150811	0.905	0.905	1
439	Roelofarendsveen	20121121	20161124	0.829	0.915	3
362	Ruinerwold	20131120	20170704	0.833	0.906	2
965	Schaesberg	20131211	20170621	0.865	0.930	1
905	St Anthonis	20151009	20170713	0.935	0.935	1
741	Stavenisse	20140501	20170629	0.818	0.889	5
91	Ternaard	20150730	20170627	0.824	0.905	2
344	Tollebeek	20131023	20170615	0.868	0.876	1
897	Venlo	20131121	20170612	0.926	0.926	1
733	Vlissingen	20130719	20170706	0.933	0.933	1
751	Vrouwenpolder	20130718	20170706	0.924	0.924	1
233	Zaandam (Hembrug)	20120628	20160404	0.914	0.964	3
917	Zaltbommel	20140306	20160503	0.913	0.913	1
372	Zeewolde (Schillinkweg)	20131016	20170615	0.776	0.892	3
470	Zegveld	20130201	20170622	0.763	0.890	3
589	Zetten	20130501	20170618	0.788	0.860	4
426	Zoetermeer	20130131	20170323	0.838	0.928	3
145	Zoutkamp	20131127	20170620	0.848	0.930	3

For 33 stations the correction was based on the simple Model 1. Models 2, 3, 4 and 5 were selected 11, 16, 2 and 3 times, respectively.

Figure 13 shows a histogram of the mean corrections. The mean correction factor varies between 0.794 (Abcoude) and 0.964 (Zaandam). The average of the mean correction factors equals 0.907. Thus the 65 stations measured on average about 9% too much rainfall. The largest correction was needed for Lemmer with a correction factor of 0.624 (in winter). This corresponds to a correction of 38 %. The comparison of rain gauges at the KNMI test site in Appendix B shows that such a large correction is not unrealistic.

Due to the large variability of the 2-monthly percentage differences and the limited length of the period of potential leakiness, leaky gauges with increases in measured rainfall < 4% are generally not detected and those with increases between 4 and 6% are only detected in six cases (see Figure 13). There remains therefore a small overestimation of about 0.5%[15] in the country-average rainfall after the applied corrections for leakiness.

[15] Making an educated guess of the overestimation of the country-average rainfall, we added 28 stations in the first bin (0-2%) of the histogram in Figure 13 with an average correction of 1%, 24 stations in the second bin (2-4%) with an average correction of 3%, and 14 stations in the third bin (4-6%) with an average correction of 5%.

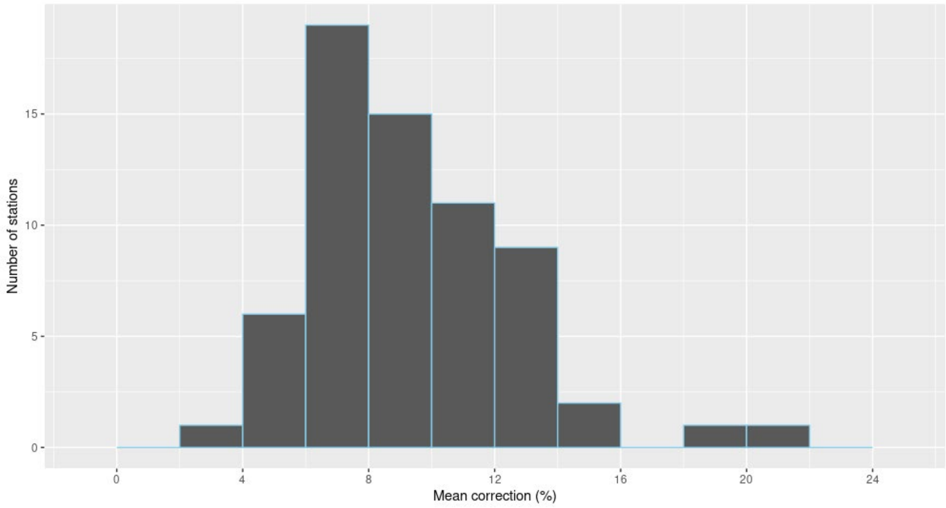

Figure 13: Histogram of the mean corrections (in percentages) in Table 1.

5. Summary and conclusions

In this report we addressed the identification of stations with leaky rain gauges in the manual daily rainfall network in the Netherlands in the 2012-2017 period and the correction of the daily rainfall amounts for these stations. We were able to divide the stations of the network in a set of stations with non-leaky gauges and a set with (potentially) leaky gauges. This was done with the help of metadata and experiments. Subsequently, the time series of 2-monthly rainfall sums of every station with a (potentially) leaky gauge (candidate station) was compared with the mean of the 2-monthly rainfall sums at the 15 nearest stations with non-leaky gauges (reference). The percentage differences between these 2-monthly rainfall sums were used to statistically assess the leakiness of a gauge. If found leaky, several statistical models were fitted to the percentage differences. These models ranged from a simple model with constant corrections to models with a linearly increasing trend combined with a seasonally varying change. For each leaky station the optimal model was selected objectively and automatically. The 2-monthly correction factors obtained from the selected model were applied to the daily rainfall series. In the end, the data from 65 of the 320 rainfall stations were corrected. On average these 65 stations measured 9% too much rainfall. The mean correction varies between 4% (Zaandam) and 21% (Abcoude). The largest correction, 38% in winter, was made for Lemmer. In the field experiment at the KNMI test site in De Bilt, similar differences between leaky and non-leaky gauges were incidentally found. The underlying daily time series of the 65 stations were corrected and replaced in the KNMI climatological database after the publication of this report. In addition, the derived operational products were adapted and republished.

Acknowledgements

Several KNMI employees were involved in the station inspections (leakiness tests and sealing of gauges), the parallel measurements and the sorting out of station metadata. This help is greatly acknowledged. The report benefitted from the review by dr. G. Kok from VSL, the Dutch National Metrology Institute (NMI).

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Appendix A: Results of the leakiness test at KNMI

Table 2 presents the results of the leakiness test at KNMI (shower test). It compares the results of the shower test with the on-site leakiness test results. Note that 9 of the 59 considered rain gauges were leaky rain gauges which could not be repaired and sealed on site owing to a shifted ring. The leakiness of these rain gauges could not be tested on site. For four of these gauges the shower test could also not be performed.

Table 2: Summary of the leakiness test results for the 59 gauges tested at KNMI (shower test) and on-site (if available).

No	Name	Leakiness (mm/min)		Notes
		On-site	**KNMI shower**	
572	Abcoude	40.0	3.6	Repaired gauge (spot welding)
910	Ammerzoden	0	0	Visually allright
543	Apeldoorn	20.0	4.8	Damaged
140	Assen	0	0	Visually allright
234	Bergen (NH)	20.0	1.0	Repaired gauge (spot welding)
25	De Kooy	1.3	0	Visually allright
354	Dedemsvaart	2.4	0.1	Visually allright
449	Delft	0	0	Visually allright
141	Delfzijl	60.0	3.0	Damaged
447	Den Bommel	1.4	0.1	Rim[16] loose
908	Deurne	0.1	0	Rim loose
911	Dinther	NA[17]	0.2	Shifted ring
161	Eelde	0	0	Visually allright
665	Enschede	30.0	1.9	Repaired gauge (spot welding)
980	Epen	5.3	0.2	Rim loose
136	Ezinge	0	0	Visually allright
584	Geldermalsen	NA	NA	Shifted ring (completely loose)
139	Groningen	0.1	0	Visually allright
434	Groot Ammers	16.0	0.8	Rim loose
752	Haamstede	24.0	6.1	Damaged
328	Heerde	0	0	Visually allright
477	Hoek van Holland Molenpad	0.9	0.1	Visually allright
480	Honselersdijk	30.0	6.5	Repaired gauge (spot welding)
438	Hoofddorp	3.4	0.5	Repaired gauge (spot welding)
222	Hoorn (NH)	0	0	Repaired gauge (spot welding)
564	Hulshorst	1.2	0	Visually allright
444	Katwijk	60.0	1.1	Repaired gauge (spot welding)
737	Kerkwerve	NA	2.8	Shifted ring
77	Kollum	NA	3.0	Shifted ring
323	Laaghalen	24.0	3.2	Visually allright
912	Leende	NA	NA	Shifted ring (completely loose)
437	Lijnden	3.0	0.6	Visually allright
454	Lisse	3.0	0.3	Visually allright
548	Loenen a/d	60.0	1.8	Visually allright

[16] The rim is the top part of the funnel at 40 cm above ground level. Just like the ring the rim is glued to the funnel. A loose rim might slightly enhance the leakiness. A missing rim enhances the rainfall by about 10% because it enlarges the gauge collecting surface from 200 cm^2 to about 220 cm^2.

[17] NA means not available.

	Vecht			
918	Maarheze	NA	NA	Shifted ring (completely loose)
479	Maasland	20.0	0.6	Visually allright
166	Marum	0	0	Visually allright
162	Niekerk	0.2	0	Visually allright
450	Numansdorp	NA	NA	Shifted ring (completely loose)
833	Oosterhout	0.2	0	Rim missing
225	Overveen	NA	0.4	Shifted ring
674	Rekken	0.5	0	Rim missing
339	Rheezerveen	0.1	0	Visually allright
163	Roden	0.7	0.1	Visually allright
961	Roermond	1.6	0.6	Visually allright
362	Ruinerwold	NA	6.9	Shifted ring
760	s-Heerenhoek	NA	1.1	Shifted ring
970	Stamproy	16.0	0.9	Ring loose but not shifted
80	Stavoren	24.0	0	Ring loose but not shifted
144	Ter Apel	2.7	0.3	Visually allright
510	Vaassen	0	0	Visually allright
474	Valkenburg	NA	1.1	Shifted ring
160	Veenhuizen	0.1	0	Visually allright
481	Voorschoten	0	0	Visually allright, few drops during the on-site test
926	Waalre	20.0	0.2	Visually allright
770	Westdorpe	0.7	0	Visually allright
226	Wijk aan Zee	60.0	0.9	Repaired gauge (spot welding)
523	Wijk bij Duurstede	0.2	0	Visually allright
666	Winterswijk Sibbinkweg	0	0	Visually allright

Appendix B: Comparison of rain gauges at the KNMI test site

Eleven manual rain gauges were compared in the period June 2017 – May 2018 at the KNMI test site in De Bilt. Two automatic KNMI rain gauges were also included in the comparison. Table 3 describes all 13 gauges.

Table 3: Description of the 13 rain gauges used in the comparison.

Gauge no.	Description	Leakiness (mm/min)	
		On-site	Shower
R1	Old type manual rain gauge	0	0
R2	Old type manual rain gauge	0	0
R3	New type manual rain gauge (glued)	0	0
R4	New type manual rain gauge (glued)	0.5	0
R5	New type manual rain gauge (glued)	23.1	6.8
R6	New type manual rain gauge (repaired using spot welding)	12.0	0.1
R7	New type manual rain gauge (repaired using spot welding)	30.0	1.7
R8	New type manual rain gauge (ring shifted upward)	NA	2.5
R9	New type manual rain gauge (ring shifted upward)	NA	2.6
R10	New type manual rain gauge (glued)	0	0
R11	New type manual rain gauge (taped with Denso tape)	0	0
R260	KNMI automatic gauge (170 m east of test site)	NA	NA
R261	KNMI automatic gauge (10 m west of test site)	NA	NA

All manual gauges were tapped daily at 8:00 UTC, except in the weekend. The Monday morning measurement concerns the rainfall amount since the preceding Friday morning 8:00 UTC. Deviations of this practice have been noted along with the measurements.

The 10-minute rainfall amounts from the automatic rain gauges were summed to 24-hour amounts over the 8:00 – 8:00 UTC interval.

For the intercomparison of the gauges, the non-leaky old type rain gauge R1

Photo 5: KNMI staff tapping the eleven manual rain gauges at 8:00 UTC.

was used as a reference. Percentage differences were calculated as:

$$PD = 100\frac{P_{\mathrm{RN}} - P_{\mathrm{R1}}}{P_{\mathrm{R1}}},$$

where P_{RN} is the rainfall of rain gauge RN and P_{R1} the rainfall of the reference gauge R1 (for the gauge numbers see Table 3).

The percentage differences of the monthly rainfall sums in Figure 14 show generally larger *PD* in the winter half-year than in the summer half- year. The largest values are found for gauge R9 with values of *PD* up to 30-40% in January and February. This gauge was one of the gauges with the ring shifted upward (this was also the situation in Lemmer when the gauge was replaced on 15 February 2015). Note that the monthly differences between the non-leaky old type gauges R1 and R2 range between 0% and 5%. On the annual level R2 is 1.6% lower than R1. For the new-type non-leaky gauges the annual values with respect to R1 are: R3 3.8% higher, R4 2.7% higher, R10 0.7% lower, and R11 2.3% higher. For the automatic gauges it is known that, especially in winter, they receive less rainfall than manual gauges (Brandsma, 2014). This can partly be attributed to the heating of the automatic gauges at low temperatures and partly to the location of manual rain gauges in more sheltered environments than the automatic ones.

For days with rainfall ≥ 5 mm we made boxplots for the daily *PD*. See Figure 15. The plots show a large variability of the daily *PD*. For instance, for gauge R7 the daily *PD* ranges between about 0 to 45%. There are two main reasons for this large range. First, as explained in Section 3.2, the leakiness depends on the orientation of the funnel (which is random from day-to-day) with respect to the wind direction.

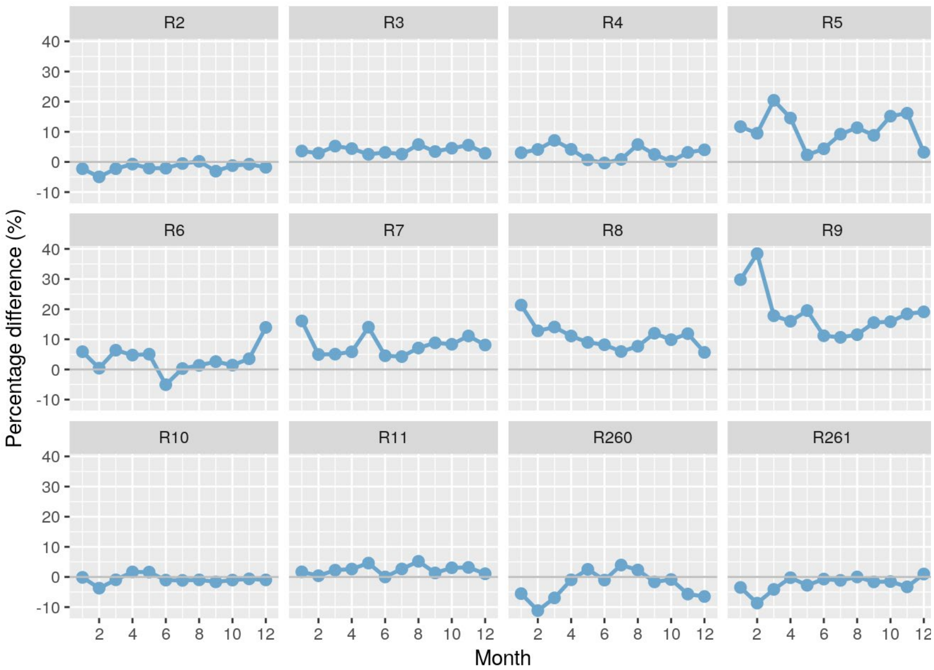

Figure 14: Monthly percentage differences PD per rain gauge with R1 as reference (June 2017 - May 2018).

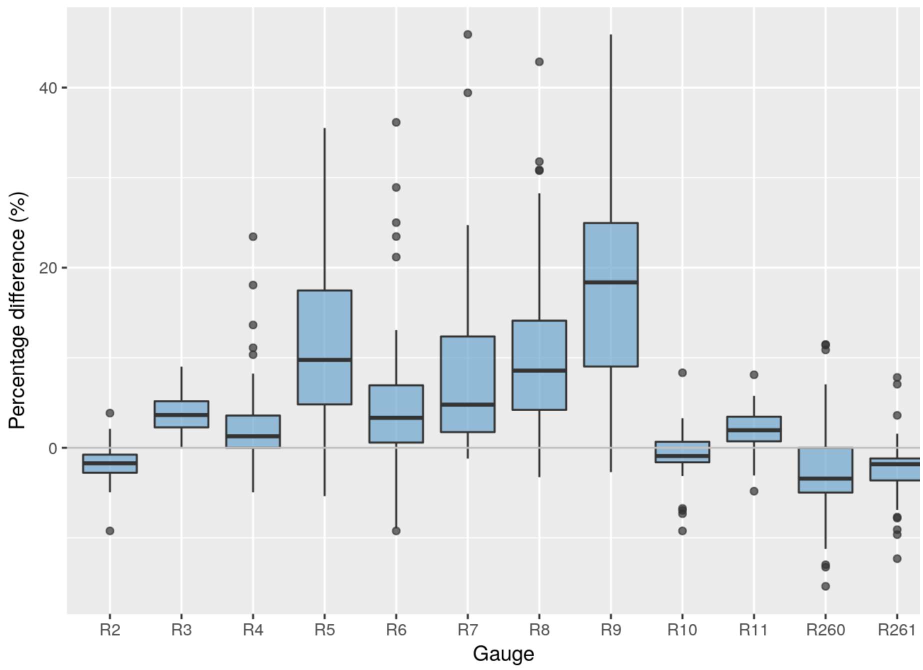

Figure 15: Boxplot of daily percentage differences for days with rainfall ≥ 5 mm at R260 (June 2017 - May 2018).

Second, the amount of water splashing against the sides of the funnel – and thus potentially reaching the reservoir of leaky gauges – depends on wind speed and rainfall intensity. Wind speed and rainfall intensity also determine the wind error of rain gauges. For De Bilt Beersma et al. (2015) showed the wind error for daily rainfall to be proportional to the mean wind speed on wet hours (FH_{wet}) and inversely proportional to the mean rainfall intensity on wet hours to the power 0.8 ($I_{wet}^{0.8}$). Both were derived from automatic rain gauge measurements.

Figure 16 shows the relationship between the daily *PD* and $FH_{wet}/I_{wet}^{0.8}$. The wind speed *FH* is measured with a cup anemometer at 2.2 m height about 40 m northwest of the test site. Rainfall intensity I_{wet} is obtained from the automatic rain gauge R261. For the leaky gauges there is a positive relationship with $FH_{wet}/I_{wet}^{0.8}$. The relationship is strongest for the leaky gauges with the ring shifted upward. Note also the slightly decreasing relationship for the automatic gauges. This could suggest a stronger increase of the wind error of the automatic gauges with $FH_{wet}/I_{wet}^{0.8}$ than the wind error of the manual gauges. However, $FH_{wet}/I_{wet}^{0.8}$ has a clear seasonal cycle with the largest values in winter and the smallest in summer. So the large values of $FH_{wet}/I_{wet}^{0.8}$coincide with the rainfall loss in winter of the automatic gauges due to the heating of these gauges.

Summarizing, the amount of water potentially reaching the reservoir of leaky rain gauges depends on wind speed and rainfall intensity. The real amount reaching the reservoir also depends on the orientation of the leaks with respect to the wind direction. As the latter is unknown, only a statistical correction of the rainfall data of stations with leaky gauges is possible.

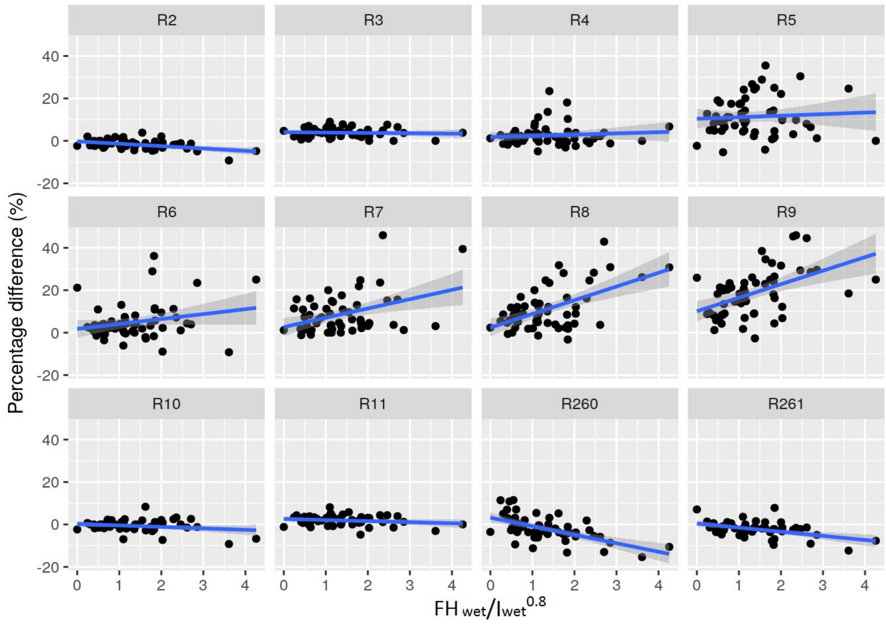

Figure 16: Relationschip between the daily percentage differences PD and the daily weather variable $FH_{wet}/I_{wet}^{0.8}$. The gray band represents the 2 × se band of the fitted regression line.

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