Bayerische Landesanstalt für Wald und Forstwirtschaft

BAYERISCHE FORSTVERWALTUNG

Literature Study on the Correction of Precipitation Measurements

FutMon C1-Met-29(BY)

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Contents

1. Introduction

Precipitation is one of the key components in hydrological modeling and water balance studies. A comprehensive, optimized and sustainable water balance monitoring requires the availability of accurate precipitation data.

Precipitation measurements however, are affected by systematic errors, which lead to an underestimation of actual precipitation. Systematic losses vary by type of precipitation (rain, mixed, snow) and gauge type. The systematic error of solid precipitation is commonly greater than the error for liquid precipitation.

For most precipitation gauges wind speed is the most important environmental factor, which contributes to the underestimation of actual precipitation, especially for solid precipitation.

In the frame of the FutMon C1-Met-29 (BY) action the correction of systematic precipitation measurement errors has the task to gather information about the different types of precipitation measurement gauges used by the participating countries and to present correction methods. In the frame of the literature study, a rain gauge questionnaire was sent out to collect some information about the different precipitation gauges and the specific measurement practices. Results revealed, that the predominant gauge type is the tipping bucket gauge and that correction procedures mainly focus on correcting data gaps, which confirms the need for the application of suitable measurement correction procedures.

The World Meteorological Organization (WMO) has organized several precipitation intercomparisons in the last decades (see Table 1) with the objective to assess and compare quantification and catching errors.

In the comparisons, reference gauges were developed (Mk 2 pit gauge for rain, the DFIR reference standard for snow) and correction procedures derived.

This study will give an overview over the different measurement instruments with its individual sources of error and provide a review of the correction methods suggested by the WMO and several other authors.

2. Instruments

Generally, there are four major types of precipitation sensors: the standard rain gauge, the tipping-bucket rain gauge, the weighing type rain gauge and optical rain gauges.

Optical rain gauges have been neglected in this study, as according to the rain gauge questionnaire, they are not used by the FutMon member countries.

The standard rain gauge consists of a funnel attached to a graduated cylinder that fits into a larger container where the accumulated water and melted snow are stored between observation times. Different shapes of gauges are used all over the world. Windshields around the gauge reduce the error caused by wind –field deformation. According to the WMO Guide to Meteorological Instruments and Methods of Observation (WMO-8, 2008) the most important requirements of a gauge are as follows:

-the rim of the collector should have a sharp edge and should fall away vertically on the inside, and be steeply beveled on the outside.

-the area of the orifice should be known to the nearest 0.5 percent and the area should remain constant while the gauge is in normal use.

- The design of the collector should prevent the in- and out splashing of rain. To achieve this, the vertical wall has to be sufficiently deep and the slope of the funnel sufficiently steep (at least 45 percent, see Figure 1).

- The construction should minimize wetting errors.
- The container is supposed to have a narrow entrance and be sufficiently protected from radiation in order to minimize the loss of water by evaporation. Gauges used in locations where only weekly or monthly reading takes place should be similar in design to the type used for daily measurements, but with a container of a larger capacity and stronger construction.
- The measuring cylinder should be made of clear glass or plastic with a suitable coefficient for of thermal expansion. Its diameter should be less than 33 percent of that of the rim of the gauge. The precision of the measurement increases with decreasing relative diameter. The graduations should be finely engraved and there should be markings at 0.2 mm intervals. A marking of the line corresponding to 0.1mm is also desirable.

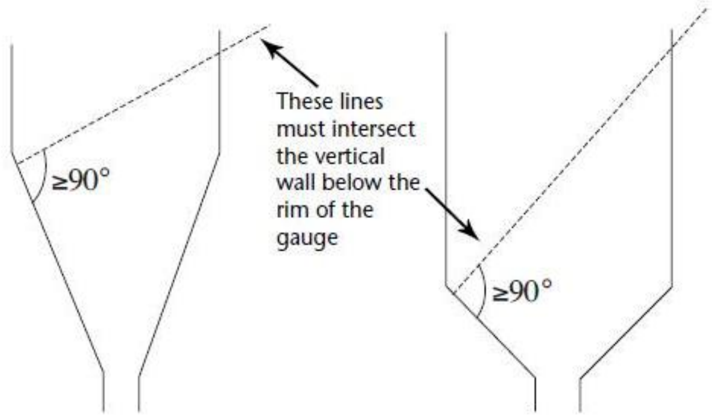

Figure 1: Suitable collector design for rain gauges (WMO-8, 2008)

A variety of different types of automatic rain gauges exists. The most common ones are weighing rain gauges and tipping bucket rain gauges. Other types include the capacitance rain gauge, (a collection- type rain gauge for potential use on buoys at sea), optical rain gauges or acoustical rainfall measurement systems. The latter will not be included in this study.
Automatic gauges (recording gauges) have the advantage that they provide better time resolution than manual measurements and that wetting and evaporation losses are (depending on the type of automatic gauge) prevented or at least reduced.
Weighing rain gauges operate on the principle of weighing the rainwater or snow collected by the instrument. Over a given time interval, the measurement of rainfall rate is the difference in rain water accumulation. Weighing gauges have to be designed to prevent excessive evaporation losses, which may be reduced further by the addition of sufficient oil or other evaporation suppressing material to form a film over the water surface.
Weighing gauges have the advantage that they can measure all kinds of precipitation.
Tipping bucket rain gauges measure rainfall by accumulating rain water in a bucket that tips and drains after a certain amount of rainwater has been collected. By tipping, a magnetic switch is triggered which sends a signal to a recording device.

2.1 Instruments used in the FutMon partner countries

In the frame of this study a questionnaire was sent out to the FutMon partners, that contained questions regarding precipitation measurement gauges and practices (see Figure 2 in the annex). The results are shown in Table 10a-c in the annex.
The evaluation of the rain gauge questionnaire revealed, that on the FutMon plots most of the meteorological measurements are carried out with tipping bucket type sensors, followed by weighing gauges. The specific sensors vary from country to country. There are no general preferences for a certain gauge system, except for the weighing gauges, where the pluvio

sensor (manufacturer: Ott, Germany) is predominantly used. Gauge measurement heights vary from 0 to 40m. At most sites the gauges are placed 1m above the ground (see Figures 3a-c). According to the questionnaire, additional wind speed and temperature measurements are available.

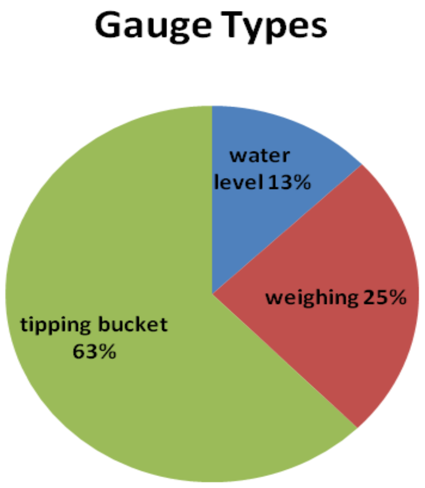

Figure 3a: Gauge types used for precipitation measurements at the FutMon forest monitoring sites (evaluation of the rain gauge questionnaire)

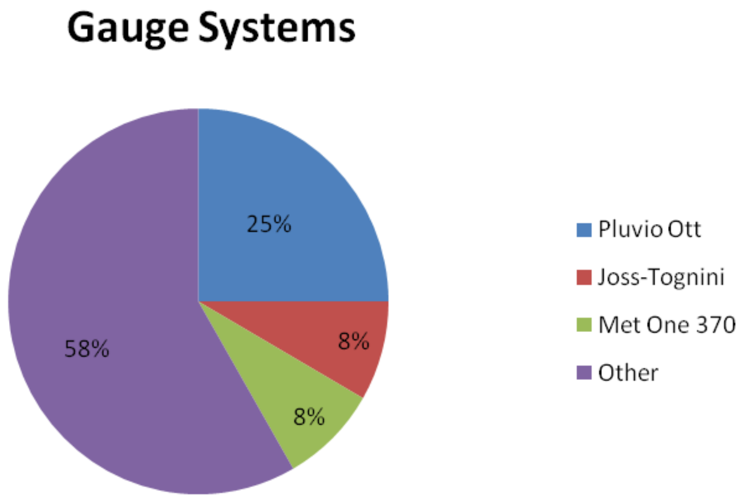

Figure 3b: Gauge systems used for precipitation measurements at the FutMon forest monitoring sites (evaluation of the rain gauge questionnaire)

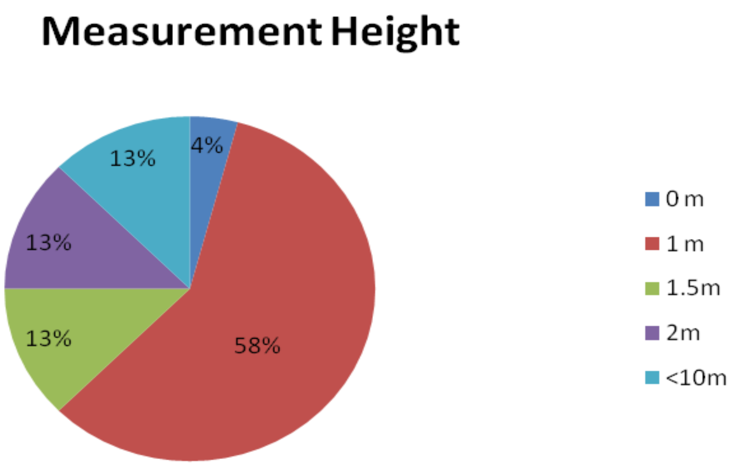

Figure 3c: Gauge heights at the FutMon forest monitoring sites (evaluation of the rain gauge questionnaire)

3. Measurement Errors

The amount of precipitation measured in a gauge is less than the actual precipitation reaching the ground. This is mainly due to systematic errors leading to losses that vary by the type of precipitation, gauge and location. The systematic error of solid precipitation is commonly larger than for liquid precipitation. Systematic errors include the error due to systematic **wind field deformation** above the gauge orifice (according to the WMO-8, 2008 about 2-10% for rain and 10-50% for snow), the error due to wetting loss on the internal walls of the collector and a wetting loss when it is emptied (according to the WMO-8, 2008 about 2-15% in summer and 1-8% in winter), errors due to evaporation from the container, especially important in hot climates (according to the WMO-8, 2008 up to 4%), the **trace precipitation error** (according to Sugiura et al. 2003 about 6-130%), the **systematic mechanical errors** (e.g.tipping-bucket gauges at high rainfall intensity during the tipping movement of the bucket), e**rrors due to in- and out-splashing** of water (according to the WMO-8, 2008 about 1-2 %) and **errors due to blowing and drifting** snow.

3.1 Wind–induced loss

Wind speed is the dominant environmental factor that leads to an under catch of precipitation, especially for snow. Wind field deformation results from the measurement instrument, which provokes a blocking of air stream leading to higher wind speeds and a higher intensity of turbulences. Caused by the aerodynamic blockage of the gauge body, the trajectories of precipitation particles become distorted in a wind through the displacement and acceleration of wind flow over the top of the gauge. The lighter particles are carried beyond the gauge opening, which results in a reduced catch. The extent of the under catch depends on the wind speed, the falling velocity of the particles, and the aerodynamic properties of the individual type of gauge (see Figure 4).
The amount of loss due to wind field deformation varies with wind speed, form and size of precipitation and aerodynamic characteristics of the gauge (Sevruk 2004).
Concerning the aerodynamic characteristics of the gauge, the following aspects have proven to be of importance:
-The height/diameter ratio
-The shape of the gauge
-The use of a wind shield/fence

-The strength and shape and slope of the outer parts of the gauge rim

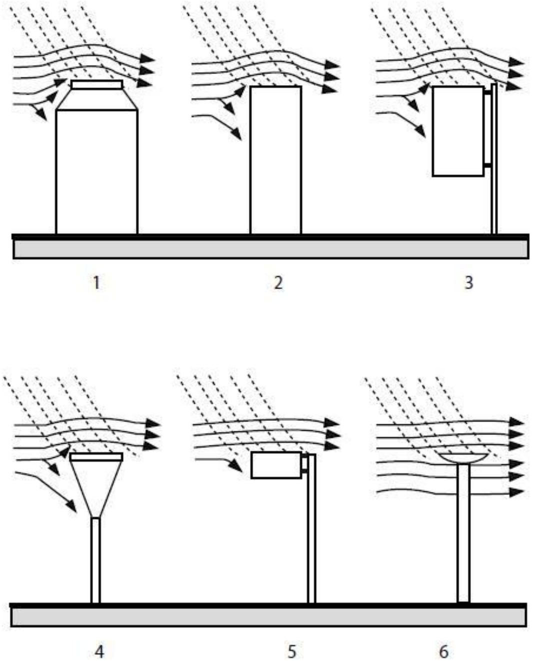

Figure 4: Different shapes of standard precipitation gauges. The solid lines show streamlines and the dashed lines show the trajectories of precipitation particles. The first gauge shows the largest wind field deformation above the gauge orifice, and the last gauge the smallest. Consequently, the wind-induced error for the first gauge is larger than for the last gauge (WMO-8, 2008).

3.2 Wetting loss

Wetting losses occur when precipitation collects on the inside walls of the gauge and evaporates (or sublimates) without being recorded. For manual gauges, wetting losses also occur while the gauge is emptied. Wetting losses depend not only on the geometry and the material of the gauge, they also vary by the type of precipitation and by the number of times the gauge is emptied (Goodison et al. 1989, Legates et al. 2005, Sevruk 1982, Sevruk 2004, Yang et al. 1999).

The ratio of walls/orifice area provides an index of the magnitude of the wetting loss. Simple cylindrical gauges show a coefficient of around 5, which relates to wetting losses of less than 0.1 mm per precipitation event. Gauges with a coefficient around 15 show wetting losses of about 0.2 mm per precipitation event (Sevruk 2004). Figure 5 shows the different indices of various gauges.

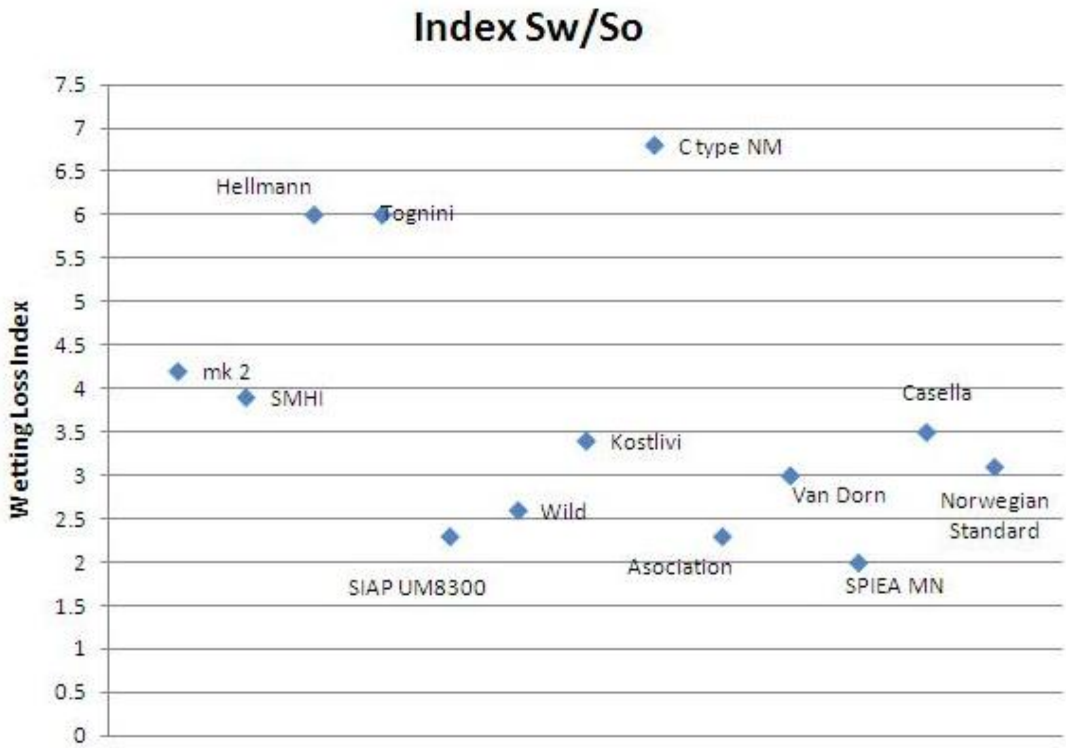

Figure 5: Indices walls/orifice (Sw/So) for different gauges (data from Sevruk 2004)

Additionally, the wetting losses are higher for gauges like the SMHI standard gauge (Swedish Meteorological and Hydrological Institute) where the container has to be emptied to measure the rainfall amount (Seibert et al. 1999).
Studies in the high-latitude regions show that the mean annual totals of the wetting loss correction in the Northwest Territories, Alaska, and Greenland were 5%–10% of the gauge-measured annual precipitation (Yang et al. 2000, Yang et al. 1998, Groisman et al. 1991).

3.3 Evaporation loss

Losses due to evaporation of precipitation between the the measurements vary by gauge type, climatic zone and time of year (Legates et al. 2005, WMO-8, 2008).
Evaporation loss is a problem with gauges that do not have a funnel device in the bucket, especially in late spring at mid-latitudes. Losses of over 0.8mm per day have been reported (WMO-8, 2008).
For the Tretyakov gauge tested at the Jokioinen experimental station in Finland evaporation losses in summer of 0.30-0.80mm per day and winter 0.10-0.20 mm per day were reported (Yang et al. 2001). For the Danish Hellmann gauge at the same site evaporation between 0.16-0.27mm per day and 0.03-0.24mm in winter have been measured (Yang et al. 1999).
Groisman et al. (1991) estimated the mean July evaporation loss 2-8% of the monthly total precipitation in Siberia, when precipitation measurements were made twice per day.
For tipping-bucket gauges water remaining in one of the buckets may evaporate before the next event and, thus, evaporation losses become more significant (Seibert et al. 1999).

3.4 Trace Precipitation

Precipitation events that are beyond the resolution of the specific gauges are considered as trace precipitation. It has been reported, that in northern regions up to 80% of the winter snowfall consisted of trace precipitation (Yang et al. 1998, Yang 2001).
Correction of trace precipitation is thus important, especially in regions of low precipitation (Sugiura et al. 2003, Yang et al. 2001).

3.5 Systematic mechanical and operational errors

Tipping-bucket gauges have sources of errors that differ somewhat from other gauge types. According to the study of Nystuen (1999), the tipping bucket rain gauge is underestimating the rainfall rate, especially during heavy rainfall events. It was assumed this was due to the water loss between the “tips” (Molini et al. 2005, Nystuen 1999, WMO-168, 1994). According to Molini et al. (2005) this bias is gauge- specific and amounts about 10-15% for rain rates higher than 200mm/h. Sevruk (1996, 2002) and Chvila et al. (2005) mention clogging of tipping-bucket gauge outflow and mechanical and electronical disturbances due to bird droppings or falling leaves. Especially in winter tipping-bucket gauges are considered to measure precipitation unreliably (Sevruk 2002, Chvila et al. 2005). Results from the WMO solid precipitation intercomparison for a site and Finland showed a large undercatch of the heated tipping bucket type autogauges, so that the use of these automated gauges cannot be recommended for northern sites (Goodison et al. 1998). Upton et al. (2003) describe blockages and high rain rates as major sources of error of tipping-bucket gauges. When the design of the bucket exposes a large water surface, losses due to evaporation can be a problem in hot regions (WMO-168, 1994). Because of the discontinuous nature of the record, the instrument is not satisfactory for use in light drizzle or very light rain (WMO-168, 1994).

Operational problems of weighing gauges include freezing rain and wet snow that sticks inside of the gauge orifice in winter. Another common fault is wind pumping: during high winds turbulent air currents passing over and around the gauge container cause oscillations in the weighing mechanism, which leads to anomalous recordings (WMO-8, 2008).

Nystuen (1999) investigated the relative performance of automatic rain gauges under different rainfall conditions. In his study, problems of the weighing gauge included the automatic siphoning system, which failed to perform correctly especially during long and high accumulation events. Chvila et al. (2005) describes a temperature dependence of measured values, and software errors in filtering out the effect of wind shocks, vibrations and sudden changes.

3.6 Other errors

Errors due to blowing and drifting snow occur especially in northern regions with a lot of snow and high wind speeds (Sugiura et al. 2003)

Errors due to the in- and out-splashing of water amount up to 1 to 2 % (WMO-8 2008).

4. Correction of precipitation measurement errors

As discussed in Chapter 3 measured precipitation is subject to errors that lead to lower catch ratios in the gauge compared to the actual precipitation that reaches the ground. Systematic errors vary by type of precipitation, wind speed, location and gauge. The evaluation of the questionnaire sent to the FutMon partner countries showed that the precipitation data used is mainly uncorrected (see Figure 6). Corrections mostly cover only the filling of data gaps. For many hydrologic purposes, however, it is necessary to estimate the true amount of precipitation. Therefore, measurement errors have to be corrected. Correction procedures described here cover only the systematic errors wetting loss, evaporation loss, trace precipitation and the wind-induced error. Errors due to splash in and splash out and errors for blowing and drifting snow will not be part of this study.

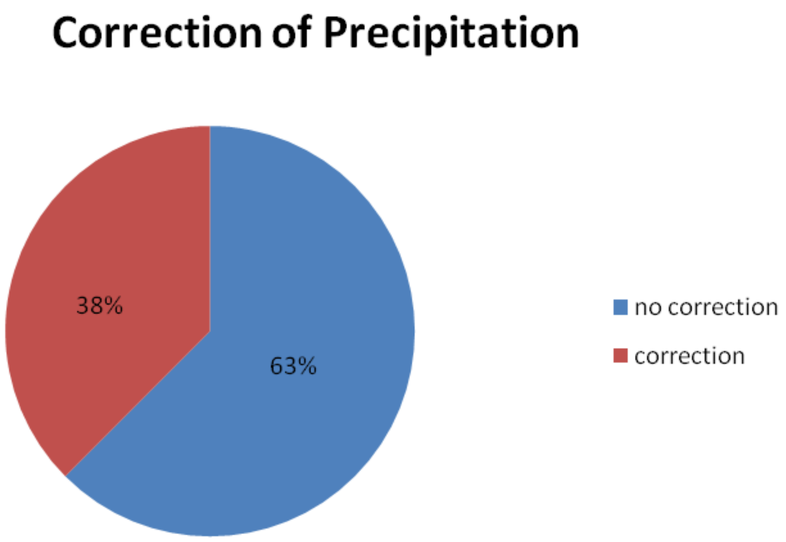

Figure 6: Correction of precipitation data at the FutMon forest monitoring sites (evaluation of the rain gauge questionnaire)

4.1 Correction for the wetting loss

According to the wetting loss experiments conducted in Russia, the average wetting loss of the Tretyakov gauge was 0.20 mm per observation for rainfall measurements and 0.15 mm per observation for both snow and mixed precipitation (Yang et al. 2000). The methods of wetting loss correction in the former USSR since 1967 are summarized by Groisman et al. (2001) as the following:

When precipitation occurs during the measurements, but there is no moisture in the gauge, no correction applies for the wetting loss.

If precipitation measurements are less than one-half of the resolution of the gauge (i.e. 0.1mm) but moisture runs out of the bucket when emptied, add 0.1 mm to rain and mixed precipitation events, but not to solid precipitation.

When the gauge measurements are greater than 0.1 mm, add 0.2 mm for rain and mixed precipitation events and 0.1 mm for snow events. Yang et al. (1999) calculate for each precipitation day an averaged wetting loss according to the type of precipitation. According to wetting loss experiments, the average wetting loss of the Hellmann gauge was 0.14 mm per observation for rain and 0.10 mm for snow (Yang et al. 1999).

Seibert and Moren (1999) in Sweden correct Hellmann gauge measurements for wetting loss by adding 0.1 mm to each precipitation event.

Sevruk (1982) suggests the following equation for the estimation of wetting loss:

$$\Delta P1 = a1 * n1$$

Where:

a1= experimentally estimated average wetting loss per event for a particular collector and form of precipitation

n1= number of precipitation events with the interval between them greater than the average time needed to dry out the internal walls of the collector (drying time).

Values for different gauges can be found in Table 7 in the annex.

For weighing gauges the wetting loss error is minimal and can be neglected (WMO-8, 2008).

4.2 Correction for the evaporation loss

Evaporation loss can be estimated as follows according to the WMO Guide to meteorological practices (No-168, 1994):

$\Delta Pe = i_e * \tau_e$

With:
i_e= evaporation intensity [mm/day]
τ_e = duration of evaporation (fractions of a day)

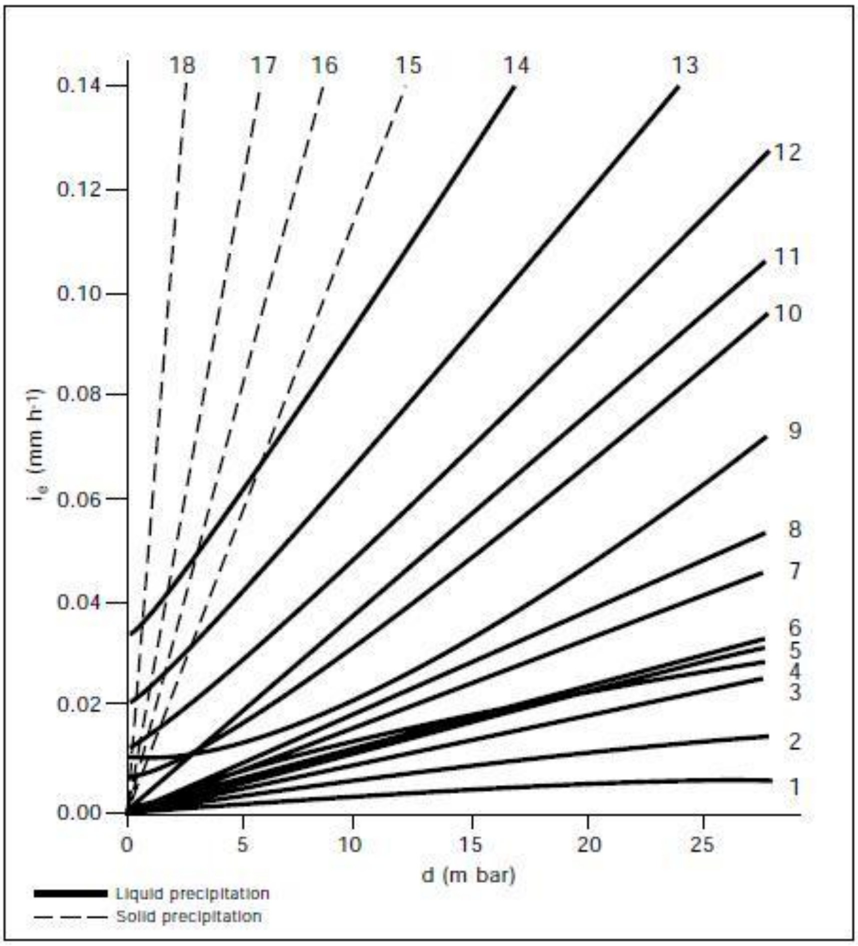

Figure 7: evaporation intensity for various gauges:
(a) liquid precipitation: (i) Australian standard gauge 1 (for P<1mm), 2 (for P 1.1 to 20mm), 7 (for P >20mm) and 11 (for wind speed >4 m/s); (ii) Snowdon gauge in a pit 3 (for P<1mm), 6 (for P 1.1 to 10mm), 8 (for P >10mm); (iii) Hellmann gauge 4, (iv) polish standard gauge 5, ,(v) hungarian standard gauge 9; tretyakov gauge 10 (wind speed at gauge rim level 0 to 2 m/s), 12 (wind speed at gauge rim level 2 to 4 m/s), 13(wind speed at gauge rim level 4 to 6 m/s), 14 (wind speed at gauge rim level 6 to 8 m/s).
(b) solid precipitation: Tretyakov gauge 15 (wind speed at gauge rim level 0 to 2 m/s),16 (wind speed at gauge rim level 2 to 4 m/s), 17(wind speed at gauge rim level 4 to 6 m/s), 18 (wind speed at gauge rim level 6 to 8 m/s).

The value of ie depends on the construction, material and colour of the gauge, on the amount and form of precipitation, on the saturation deficit of the air and on wind speed at the level of the gauge rim during evaporation. The theoretical estimation of the evaporation intensity (i_e) is difficult because of the complex configuration of a precipitation gauge. However, i_e can be computed using empirical equations or graphical functions (see Figure 7).
In northern regions evaporation losses can be neglected (Sevruk 1974).
For weighing gauges the evaporation loss error is minimal and does not have to be considered (WMO-8, 2008).

4.3 Correction for the trace precipitation

Yang et al. (2001) corrects trace precipitation loss on a daily basis adding 0.1mm for any given trace day. Woo and Steer (1979) designed a method of measuring trace rainfall in the Canadian high Arctic and determined a mean rate of 0.01 mm per day.

4.4 Correction for systematic mechanical and operational errors

The losses of snow and rain due to freezing are hard to tackle as the use of heated instruments is not recommended due to the high evaporation losses that occur as a consequence of the heating (Goodison et al. 1998). Anomalous recordings due to wind pumping for weighing gauges can be minimized by using programmable data loggers that average readings over short time intervals (1 min suggested by WMO-8, 2008). For tipping-bucket gauges with their specific errors special precautions and corrections are advisable. The loss of water between the tips in heavy rain can be minimized but not eliminated. Especially in light rain evaporation loss can occur and therefore needs to be corrected. Lanza and Stagi (2008) report from the WMO laboratory intercomparison, that tipping-bucket rain gauges, after proper calibration, can show an accurate performance. Recommendations for malfunctioning tests can be found in Upton et al. (2003).

4.5 Correction for wind induced gauge undercatch

4.5.1 Correction according to the WMO Precipitation Intercomparisons

The World Meteorological Organization (WMO) has organized several precipitation intercomparisons in the last decades (see Table 1) with the objective to assess and compare quantification and catching errors.
In the frame of these studies, general models for data adjustment from various gauges take the form:

$$Pk=k*Pc=k*(Pg+ \Delta P1+\Delta P2+\Delta P3)$$

Where:
k= adjustment factor for the effects of wind field deformation
Pc= the amount of precipitation caught by the gauge collector
Pg= the measured amount of precipitation in the gauge
P1=the adjustment for the wetting loss
P2= the adjustment for evaporation from the container
P3= trace precipitation

For the adjustment of gauge measurement for any wind induced bias, wind speed at gauge height is required. If wind speed is not measured at gauge height then the station wind speed can be used to estimate the wind at gauge orifice height. The following equation is used for this adaption (Goodison et al. 1998):

$U_h = [\log (h/z_0)/(\log(H/z_0)]*U_H$
With:
U_h= wind speed at the height of the gauge orifice
h= height (m) of the gauge orifice above the ground
z_0 = roughness length: 0.01 for winter and 0.03 for summer [m]
H = height of the wind speed measuring instrument above the ground [m]
U_H = wind speed measured at the height H above the ground [m/s]

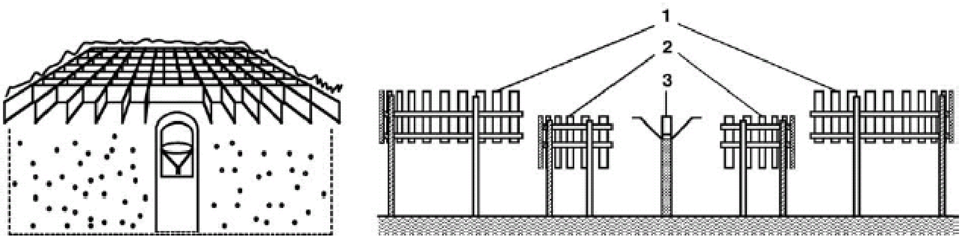

Figure 8 (Sevruk et al. 2009): Standard reference gauges used during the second and third WMO international precipitation measurement intercomparisons: the pit gauge (on the left) and the Double –Fence International Reference (right)

The objective of the **WMO Precipitation Rain Intercomparison 1972-1976** (Hamon and Sevruk 1984) was to evaluate wind correction factors for rainfall and to develop correction procedures of systematic errors using the pit gauge surrounded by the antisplash protection as the WMO standard reference (see Figure 8).
The correction for the wind induced error was based on an empirical model using wind speed and the intensity of precipitation (Sevruk and Hamon 1984). Equations that are routinely used for the estimation of the conversion factor k for the Tretyakov gauge and the Hellmann gauge are:

Tretyakov gauge (valid for monthly precipitation):
$k= 100/ [100-(0.038 N*u_{hp})]$

With:

N= proportion of precipitation totals falling at intensity ip< 0.003 mm/min [%]. Values for N can be found in Table 8 in the annex.
u_{hp} = wind speed during the precipitation at the level of the gauge orifice [m/s]

Hellmann gauge (valid for daily precipitation):

$k= \exp \mathbf{[}(-0.001 \ln (i_{pd}) – [(-0.0082* up* \ln (i_{pd})] + [(0.042 *u_{p)} + 0.01]\mathbf{]}$

With:
i_{pd} = daily rainfall intensity (mm/h)
u_p = wind speed during the precipitation at a height of 10-12 m above the ground[m/s]

Equations for various other gauges can be found in Table 9 in the annex.

Table1: The WMO international precipitation measurement intercomparisons (WMO field intercomparison of rainfall intensity gauges 2009).

Comparison	I	II	III	IV
Subject	Precipitation	Rain	Snow	Rain intensity
Period	1955–1975	1972–1976	1986–1993	2004–2008
Purpose	Reduction coefficients between the catches of various types of national gauges	Rain catch differences between various types of national gauges and the pit gauge (Fig. 1). Correction procedures developed	Wind-induced error and standard correction procedures. (Wetting and evaporation losses considered)	Performance of different principles used to measure rainfall intensity (inherent mechanical and electronic errors)
Reference standard (Fig. 1)	Mk 2 gauge[a] elevated 1 m above the ground and equipped with the Alter wind shield	Pit gauge (Mk2)[a] installed in a pit, the orifice flush with ground and surrounded by anti-splash grid	Double-Fence Inter-national Reference, DFIR (Fig. 1)bc	Calibration in three independent laboratories in France, Italy and Netherlands for different rain intensities and field tests in Italy
Participants	Belgium, Czecho-Slovakia, Hungary, Israel, USA, Russia	Basic stations: 22 countries. Evaluation stations: Australia, Denmark, Finland, USA	Canada, China, Croatia, Denmark, Finland, Germany, Norway, Russia, Sweden, USA	12 tipping-bucket gauge models, 5 weighing gauges and 2 water level gauges, all from 15 countries[d]
Results	Non-conclusive	Wind-induced loss depends on wind speed, rain intensity and type of gauge. It amounts on average to 3% (up to 20%) and to 4–6% if wetting and evaporation losses are accounted for	Wind-induced loss depends on wind speed, temperature and type of gauge. Non-shielded gauges show greater losses as shielded ones (up to 80% vs. 40% for wind speed of 5 m/s and $t > -8$ °C)	Tipping-bucket gauges where no proper correction software was applied had larger errors than the weighing gauges. Problems of water storage in the funnel also occurred that could limit the range of measurements
Reference	Poncelet (1959) Struzer (1971)	Sevruk and Hamon (1984)	Goodison et al. (1998)	Lanza et al. (2005)

[a] British Meteorological Office standard gauge of Snowdon type.
[b] The Tretyakov gauge is the Russian standard gauge.
[c] The diameter of inner fence is 4 m and of the outer fence is 12 m. The respective heights are 3 and 3.5 m above ground (Fig. 1). The Tretyakov gauge without fence is the secondary standard.
[d] Australia, Austria, Canada, Czech Republic, Finland, France, Germany, India, Italy, Japan, Norway, Slovakia, Switzerland, UK, USA. The types of gauges are shown in Sevruk and Klemm (1989).

A more sophisticated correction method for liquid precipitation developed in the frame of the precipitation intercomparison, which is based on numerical simulation is presented by Nespor and Sevruk (1999).

The **WMO solid precipitation intercomparison (1986-1993)** project (Goodison et al. 1998) had the aim to determine the wind-induced error of different shielded and unshielded national standard gauges (the Russian Tretyakov Gauge, the Hellmann Gauge, the Canadian Nipher Gauge, and the US NWS 8”standard gauge) and to derive correction procedures for solid and mixed precipitation. The analysis was based on the combined international data set collected by the WMO Solid Precipitation Measurement Intercomparison project (Goodison et al. 1998).

Regression analysis was used to develop relationships of catch ratio versus wind and temperature.

For all gauges and at all sites, it was confirmed that wind is the most dominant environmental variable affecting the gauge catch efficiency. Temperature had a much smaller overall effect on the catch ratio, and was found to be more important for mixed precipitation than for snow. Using the Multiple Linear Regression results as a guide, non linear regression analysis was applied to obtain improved fits where appropriate.

The final regression equations (based on combining data from sites in different climatic regimes) for catch ratio versus wind and temperature for the four gauges are given in Table 2. Once daily wind speed at gauge height is determined, the daily catch ratio (CR, %) for the specific gauge is calculated using one of the regression equations for snow and mixed precipitation. The wind loss correction coefficient k is calculated: k=100/CR.

Bias correction should be conducted on a daily basis (Goodison et al. 1998, Yang et la. 2001). For solid precipitation, gauge undercatch at the same wind speed is considerably higher than for rain, so that a classification of precipitation in solid and liquid is mandatory. Several studies use air temperature values as classification criterion. Yang et al (2001) uses thresholds of -2°C for snow, -2 to 2°C for mixed precipitation and 2 ° C for rain in his study in Siberia.

Table 2 (Goodison et al. 1998): Regression equations (based on combining data from sites in different climatic regimes) for catch ratio versus wind and temperature for the four gauges

Gauge	Catch Ratio versus Wind and Temperature	n	r^2	SE
	Snow			
Nipher	$CR_{NIPHER} = 100.00 - 0.44*W_s^2 - 1.98*W_s$	241	0.40	11.05
Tretyakov	$CR_{Tretyakov} = 103.11 - 8.67 * W_s + 0.30 * T_{max}$	381	0.66	10.84
US NWS 8" Sh.	$CR_{NWS\ 8\text{-}Alter\ Shield} = \exp(4.61 - 0.04*W_s^{1.75})$	107	0.72	9.77
US NWS 8" Unsh.	$CR_{NWS8\text{-}unshield} = \exp(4.61 - 0.16*W_s^{1.28})$	55	0.77	9.41
Hellmann	$CR_{Hellmann,\ unsh.} = 100.00 + 1.13*W_s^2 - 19.45*W_s$	172	0.75	11.97
	Mixed			
Nipher	$CR_{NIPHER} = 97.29 - 3.18*W_s + 0.58* T_{max} - 0.67*T_{min}$	177	0.38	8.02
Tretyakov	$CR_{Tretyakov} = 96.99 - 4.46 *W_s + 0.88 * T_{max} + 0.22*T_{min}$	433	0.46	9.15
US NWS 8" Sh.	$CR_{Alter\ Shield} = 101.04 - 5.62*W_s$	75	0.59	7.56
US NWS 8" Unsh.	$CR_{Unshield} = 100.77 - 8.34*W_s$	59	0.37	13.66
Hellmann	$CR_{Hellmann,\ unsh.} = 96.63 + 0.41*W_s^2 - 9.84*W_s + 5.95 * T_{mean}$	285	0.48	15.14

The WMO intercomparison method has been applied in various forms by a variety of authors and different sites (Bogdanova et al. 2002, Michelson 2004, Milkovic 2002, Rubel and Hantel 1999, Yang et al. 1999, Yang et al. 2001, Yang et al. 2005).
Yang et al. (1999) use the following equation for bias correction of daily Hellmann gauge precipitation measurements for Greenland:

$Pc=K(Pg+\Delta Pw+\Delta Pe)+ \Delta Pt$

With
Pc= corrected precipitation
Pg = gauge measured precipitation
ΔPw = wetting loss
ΔPe= evaporation loss
ΔPt =trace precipitation

K=100/CR

CR Snow: $100.00-11.95Ws+0.55Ws^2$ ($0 \leq Ws \leq 6.5$m/s)

CR Mixed: $100.00-8.16Ws+0.45Ws^2$ ($0 \leq Ws \leq 6.5$m/s)

CR Rain: $100.00-4.37Ws+0.35Ws^2$ ($0 \leq Ws \leq 6.5$m/s)

With Ws = daily windspeed [m/s]
Michelson (2004) used the DCM Dynamic Correction Model (Forland et al. 1996) for SYNOP precipitation measurements from gauges found in and near the Baltic Sea's drainage basin, and evaluated the implementation with two years of independent data from a DFIR station at Jokioinen, Finland and with one year of measurements from Kiel, Germany. He used a correction factor k for different types of precipitation and for the adaption on various gauges a gauge coefficient c.

The following equations have been used:

$P_c = k(Pm+\Delta Pw+\Delta P_E)$

With
k = is the correction factor for wind
Pm=measured precipitation
ΔPw= wetting loss according to Table 3
ΔPE=evaporation loss according to Table 4

For the determination of k the precipitation phase has to be taken into account.

For liquid precipitation:
$k= \exp[-0.00101*\ln(I)-0.012177*v_g*\ln(I)+0.034331*v_g+0.007697+c]$

where
I= rain intensity (mm/h)
v_g= wind speed (m/s) at gauge height
c = gauge coefficient (Table 5)

For solid precipitation:
$k = \exp[\beta_0 + \beta_1*v_g+ \beta_2*T+ \beta_3*v_g*T]$ for $v_g > 1.0$m/s

$k = 1.0$ for $v_g \leq 1.0$m/s

β_i = gauge coefficients in (Table 5)
v_g = wind speed at gauge height (m/s)
T = temperature (°C)

For mixed precipitation:

$k = (r_l*k_l+r_s*k_s)/(r_l+r_s)$

With:
k_l and k_s correction factors for liquid or solid precipitation,and r_l and r_s are the precipitation amounts in liquid and solid form, respectively.

Table 3 (Michelson 2004): Wetting constants per case (mm/12h) for each gauge type and precipitation phase. The values are divided by the number of hours with precipitation per 12h SYNOP term

Precip. phase	SMHI	H & H-90	Hellmann	Tretyakov
Liquid	0.07	0.13	0.14	0.14
Solid	0.02	0.05	0.10	0.09
Mixed	0.06	0.11	0.18	0.14

Table 4 (Michelson 2004): Daily evaporation loss constants for each gauge type (mm/day). These values are divided by 24 to arrive at hourly losses

Month	SMHI	H & H-90	Hellmann	Tretyakov
January	0.02	0.03	0.01	0.03
February	0.03	0.04	0.02	0.04
March	0.04	0.06	0.03	0.05
April	0.12	0.20	0.04	0.22
May	0.10	0.04	0.09	0.13
June	0.15	0.05	0.15	0.15
July	0.15	0.05	0.16	0.15
August	0.10	0.05	0.08	0.10
September	0.05	0.04	0.02	0.05
October	0.03	0.03	0.01	0.03
November	0.03	0.03	0.01	0.03
December	0.02	0.03	0.01	0.03

Table 5 (Michelson 2004): gauge constants for liquid and solid precipitation for each gauge type and case (mm/12h)

Precip. phase	SMHI	H & H-90	Hellmann	Tretyakov
Liquid	−0.05	−0.05	0.0	−0.05
Solid β_0	−0.08871	−0.07556	0.04587	−0.04816
Solid β_1	0.16146	0.10999	0.23677	0.13383
Solid β_2	0.011276	0.012214	0.017979	0.009064
Solid β_3	−0.00877	−0.007071	−0.015407	−0.005147

4.5.2 Correction method according to Sevruk (2004)

A correction procedure for monthly precipitation data from Hellmann gauges is suggested by Sevruk (2004).
The application of the correction is recommended for:

-monthly precipitation of climate stations and automatic stations
-reliable, homogenous data sets without gaps
-for Hellmann-type precipitation gauges with a measurement height of at least one meter above the ground (for e.g. Germany, Poland, Denmark, Switzerland-the correction procedure can be adapted for other measurement gauges, however)
-sites, where evaporation losses can be neglected
-sites, where simplification for the determination of the necessary variables is possible
-snowdrift and splashing are not of major importance

The corrected sum of monthly precipitation can be calculated according to Sevruk (2004):

$N_k = k (N_g + \Delta N_{2+3})$

With:

N_k=corrected monthly precipitation [mm]
k = wind related conversion factor (see Table 11 in the annex)

N_g= measured monthly precipitation [mm]
ΔN_{2+3}= wetting losses of the gauge

Because wetting losses are dependent on the type of precipitation (rain or snow) they are calculated by using the fraction of snow on total precipitation:

ΔN_{2+3}= 0.15q[2-(Q/100)]
Q = number of precipitation days
Q = fraction of snow (%)
0.30, 0.15 = mean daily wetting loss in mm for rain and snow, respectively

Values for k can be taken from Table 11 in the annex. The listed values have been derived experimentally and can be interpolated linearly.
$N'_{0.3}$ = rain structure parameter
Q = fraction of snow for monthly precipitation sum [%]
u_{hp} = wind speed during the precipitation event at gauge height [m/s]

The rain structure parameter $N'_{0.3}$ can be calculated with the following equation:
$N'_{0.3}$= 145-(53* log (t*N/q))

With
N = monthly precipitation amount [mm]
T = monthly air temperature [°C]
q = number of precipitation days per month

4.5.3 Correction method according to Richter (1995)

A correction procedure for precipitation measurements without wind speed data has been developed by Richter for the German measurements network.
The simple correction function for daily precipitation values is the following:
P_{korr}=P + ΔP

With:

$\Delta P = b*P^{\varepsilon}$

With:
P= measurement value of Hellmann gauge
b= coefficient for the influence of wind exposition of the measurements site
ε= empiric coefficient for the precipitation type

For the development of the correction, the wind loss, the wetting loss and evaporation have been taken into account. It is based on long-term comparative measurements between Hellmann gauges in standard position and Hellmann gauges in ground-level position at 25 locations. The type of precipitation and the wind exposure situation have been defined as influencing factors. Although wind speed is a crucial factor for wind losses, it has been neglected because of the lack of accurate wind speed measurements at most of the weather station sites. The wind exposition can be estimated by considering the mean horizon shielding which is the shielding of the ceiling by trees, buildings and terrain.
Values for the coefficients b and ε are listed in Table 6.

Table 6 (ATV-DVWK-M-504 2001): Coefficients and b for precipitation correction according to Richter 1995

Precipitation type	coefficient	Coefficient b for shielding of the horizon of			
	ε	2°	5°	9.5°	16°
		open space	light shielding	medium shielding	heavily shielded
rain (summer)	0.38	0.345	0.31	0.28	0.245
rain (winter)	0.46	0.34	0.28	0.24	0.19
mixed precipitation	0.55	0.535	0.39	0.305	0.185
snow	0.82	0.72	0.51	0.33	0.21

4.5.4 Correction method according to Chang and Flannery (1998)

A method for wind correction that uses the size of raindrops and the angle of raindrop inclination is presented by Chang and Flannery (1998):

$P_t = P_o / \cos \alpha$

With
P_t=corrected precipitation
P_o= observed precipitation
α = angle of raindrop inclination due to wind effects

The angle of raindrop inclination due to wind effects is calculated as follows:
$\alpha = \tan^{-1}(V_h/V_t)$

With:
V_h = horizontal wind speed
V_t = terminal drop velocity

The terminal drop velocity (V_t) is a function of drop diameter and can be found from List (1971).

5. Conclusions and Recommendations

Accurate precipitation data is needed for all kinds of hydrologic purposes. Due to systematic losses of precipitation gauge measurements there is a need for error correction procedures. Systematic errors include wetting loss, evaporation loss, wind induced loss, trace precipitation loss and errors due to improper calibration of automatic gauges.

In the frame of this study, a questionnaire has been sent out to the FutMon member countries to receive some knowledge about the gauge systems that are used and about correction procedures of precipitation data.

The evaluation of questionnaires has revealed that the most used gauge types are the tipping bucket gauges (63%) and the weighing gauges (25%). The gauges used are different models from various manufacturers. The predominant gauge type for weighing gauges is the pluvio gauge (manufacturer: Ott, Germany). Gauge measurements heights vary from 0 to 40m; in general precipitation is mostly measured at 1m. For all sites wind speed and temperature measurements are available. Apart from one member country, no wind shields are installed.

At most sites the precipitation data is uncorrected, some sites correct data gaps.

In this study, an overview over various correction methods is presented. The correction procedures are gauge dependent, as different gauge types have different weaknesses. Weighing gauges with short intervals are not subject to evaporation and wetting loss, as the weight is measured continuously. For tipping bucket gauges proper calibration has shown to be of great importance. The wind-induced error affects all gauge types except pit gauges.

Several methods for wind induced error correction are presented in this study.

Most of the methods are based on the **WMO precipitation comparisons** carried out between **1972 and 1993**. The methods are based on catch ratios between various standard gauges and WMO reference gauges. A disadvantage of this approach is that the adaption for other gauge types apart from the standard gauges is difficult as they vary in size and shape. Another correction method is presented by **Richter (1995)**, which can be applied without wind speed data and which considers the shielding of the measurement site. Furthermore, a method suggested by **Sevruk (2004)** is presented for the correction of monthly precipitation data developed for Switzerland. **Chang and Flannery (1998)** use the size of raindrops and the angle of raindrop inclination for precipitation measurement correction.

As the wind induced error strongly depends on the site surrounding, the prevailing wind speeds and the specific gauge form, it is difficult to recommend a specific method. More research needs to be conducted in this subject. To eliminate the wind field deformation first place, it is recommended to use the WMO reference gauges (the pit gauge for liquid precipitation and the DFIR reference gauge for solid precipitation, see Figure 8). For solid precipitation it is recommended to use a wind shield, which can reduce catch losses of precipitation in winter dramatically.

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6. Annex

Table 7 (Sevruk 1982): Average wetting loss per event and day for liquid precipitation and different gauge collectors and containers, allowing one measurement of precipitation per day

Type of gauge	Country	Wetting loss per event ($P_g > 1$ mm)		Wetting loss per day
		Container a_1 (mm)	Collector a_2 (mm)	Container + Collector $\bar{a}_{1,2}$ (mm)
Association	France	0.10	0.04	0.20*
Australian - 203 mm	Australia	0.01		0.02*
Czechoslovakian	Czechoslovakia			0.30*
Dutch	Holland	0.10	0.08	0.25*
Finnish	Finland (U.S.S.R.)	0.20		0.25*
Hellmann	Denmark Fed. Rep. of Germany Switzerland	0.15	0.10	0.30
Hungarian	Hungary			0.30*
IRPG	WMO			0.20*
IRM	Belgium	0.05	0.15	0.25*
Polish	Poland			0.30*
Snowdon Mk 2	U.K.	0.10	0.06	0.20*
Snowdon Mk 1	New Zealand			0.25*
Swedish SHMI	Sweden	0.20		0.30*
Tretyakov	U.S.S.R.	0.20		0.30
U.S. (8 inch)	U.S.A.	0.10		0.15*
Wild	Bulgaria	0.10		0.20*
Belford	U.S.A.	0.15		0.20*
Fisher & Porter	U.S.A.	0.18		0.25*

NOTES: (1) a_1 and a_2 are based on laboratory tests by various authors as shown in Annex V.

(2) The given values should be reduced by half for precipitation amounts smaller than 1 mm, as well as for solid precipitation and by one-third for mixed precipitation.

Table 8: Equations used for the estimation of the parameter N for rain structure from monthly sums

Equation	No.	Reference	Symbols	
actual monthly values:				
$N = 45\text{-}75 \log i_p$	/T-9/	Bogdanova (1971)	e	mean monthly air humidity, in (mbar)
$N = 141\text{-}131\ i_p + 48\ i_p^2 - 6 i_p^3$	/T-10/	Sevruk (1981)	i_p	monthly rainfall intensity, in (mm/h)
			M	monthly number of precipitation days
multi - year averages:			N	proportion of precipitation totals falling at intensity $i_p < 0.003$ mm/min, in (%)
$N = 95 - 3.4\ t$	/T-11/	Golubev (1979)		
$N = 145 - 53 \log \left(\frac{P_g t}{M}\right)$	/T-12/	Sevruk (1981)	P_g	measured amount of precipitation in the gauge, in (mm)
$i_p = 0.38 + 0.00452\ et$	/T-13/	Bogdanova (1975)	t	mean monthly air temperature, in (^oC)

Table 9(Sevruk and Hamon 1984): Equations that are routinely used for the estimation of the conversion factor k

Tretyakov gauge (USSR): $k = \frac{100}{100-0.038\ Nu_{hp}}$	/T-1/ Bogdanova (1966)	i_{pd} = daily rainfall intensity, in (mm/h)
Nipher gauge (USSR): $k = \frac{100}{100-0.033\ Nu_{hp}}$	/T-2/ Bogdanova (1966)	k = conversion factor for liquid precipitation
Wild gauge (Finland) k = const. = 1.015 (average value for 30-year period)	/T-3/ Solantie (1978) (In: Sevruk, 1982a)	N = (See Table 2)
Wild gauge (Bulgaria): $k = \frac{100}{100-(0.031N + 1.943)u_{hp}}$	/T-4/ Subeva at al. (1980)	u_{hp} = wind speed during the precipitation at the level of the gauge orifice in (m/sec)
Hellmann gauge: $k = \exp(-0.001 \ln i_{pd} - 0.0082\, u_p \ln i_{pd} + 0.042\, u_p + 0.01)$	/T-5/ Allerup and Madsen (1980)	u_p = wind speed during the precipitation at a height of 10-12 m above the ground
$k = f(u_{hp}, N)$ graph	/T-6/ World Water Balance (1978)	u_p^* = u_p at a height of 2m above the ground
Australian gauge - 203 mm: $k = 1 + 0.015\ u_p^*$	/T-7/ Tauman et al. (1980)	Note: Equations /T-5/T-7/ and /T-8/ are valid for daily amount of precipitation. The other equations are valid for monthly sums of precipitation (see Sevruk 1982a, for details)
Swedish gauge: $k = 1 + \frac{0.002\ P_g\ u_p^2 + 0.1}{P_g}$	/T-8/ Dahlström et al. (1982)	

Rain gauge measurement system questionnaire

First name: Surname:
Institution:
Country:

Gauge system (e.g.Hellmann): Manufacturer:

Comments:

Type (e.g. tipping-bucket): Other:

Sampling orifice (collecting area): cm Comments:

Material (e.g. galv.iron): Comments:

Measurement height: (m) Comments:

Shielded? Yes: ☐ No: ☐

shield type (e.g. Nipher wind shield):

Description of surroundings (e.g. clearing, open space):

Distance to next obstacle: (m)

Height of obstacle: (m)

Comments:

Reported precipitation is corrected: Yes: ☐ No: ☐

Correction method:

1

Rain gauge measurement system questionnaire

Additional meteorological measurements at the station:

Wind speed: Yes: ☐ No: ☐ temperature: Yes: ☐ No: ☐

Comments:

Contact person in charge of meteorological measurements:

First name: Surname:
Institution:
Address:
Postal Zip: Town:
E-mail: Phone:

Comments:

Please return the questionnaire **before 11/06/2009** to Annette.Wagner@lwf.bayern.de

Annette Wagner, Bavarian State Institute of Forestry

Dep. 2 Forest Ecology, Unit 2.2 Climate and Water Protection

Am Hochanger 11, 85354 Freising, Germany

Phone: 0049/8161/71-2628

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Figure 2: FutMon literature study questionnaire

Table 10 a: Evaluation of FutMon literature study questionnaire

Country	Institution	Gauge System	Manufacturer	Type	Sampling Orifice Area [cm³]	Funnel Diameter [mm]
Austria	Federal Research and Training Centre for Forests, Natural Hazards and Landscape	Pluvio²	Ott	weighing	400	
Belgium	Research Institute for Nature and Forest (INBO)	NINA	Siggelkow GMBH Germany	tipping bucket	200	
Czech Republic	Forestry and Game Management Institute	Met One 370	MetOne, Oregon, USA	tipping bucket	320	
Denmark	Forest and Landscape Denmark, University of Copenhagen		PRENART Equipment ApS	tipping bucket	125	
Estonia	Centre of Forest Protection and Silviculture	Tretyakov		water level	200	
France	ONF (French Forest Board)	Joss-Tognini	Lambrecht	tipping bucket	200	
Germany	Landesamt für Umwelt- und Arbeitsschutz	Hellmann	Thies	tipping bucket	200	
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft	Pluvio	Ott	weighing	200	160
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft	Ombrometer	Thies	tipping bucket	200	
Germany	LANUV NRW	Pluvio	Ott	weighing	200	
Germany	Northwest German Forest Research Station	Niederschlagsgeber	Thies	tipping bucket	200	
Germany	Northwest German Forest Research Station	Pluvio	Ott	weighing	200	
Germany	Northwest German Forest Research Station	Münden100	Kautex	water level	100	
Germany	Brandenburg LFE	Joss-Tognini	Lambrecht	tipping bucket	200	
Germany	Landesforstanstalt M-V	equales to WMO No. 8	unknown	tipping bucket	200	
Germany	Thüringer Landesanstalt f. Wald, Jagd und Fischerei (TLWJF)	Pluvio1	Ott	weighing	200	
Germany	FVA-Freiburg	F&C		tipping bucket	200	
Germany	FVA-Freiburg	EM		tipping bucket	507	
Germany	Bavarian State Insitute of Forestry	Pluvio	Ott	weighing	200	
Great Britain	FOREST RESEARCH	ARG100 AERODYNAMIC	ENVIRONMENTAL MEASUREMENTS LTD	tipping bucket		254
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)		RWMUNRO LTD	tipping bucket	323	
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)		Environmental Measurements	tipping bucket	500	
Latvia	Latvian State Forestry Research Institute "Silava"	WS 3650	LA CROSSE TECHNOLOGY	water level		150
Slovakia	National Forest Centre	Met One 370	Met One, Oregon, U.S.A.	tipping bucket	320	

Table 10b: Evaluation of FutMon literature study questionnaire

Country	Institution	Material	Measurment Height [m]	Shielded	Shield Type	Description of Surroundings
Austria	Federal Research and Training Centre for Forests, Natural Hazards and Landscape	base plate: stainless steel, aluminium, bucket: polyethylene, pipe housing: ASA (Acrylester-Styrol-Acrylnitril)	1	no		clearing or open space
Belgium	Research Institute for Nature and Forest (INBO)	galv. iron	40	no		tower above canopy
Czech Republic	Forestry and Game Management Institute	galv. iron, tipping bucket coated by teflon	1	no		usually open space
Denmark	Forest and Landscape Denmark, University of Copenhagen	polyethylene	2	no		In clearing or nearby open field outside the forest
Estonia	Centre of Forest Protection and Silviculture	galv.iron	2	yes	Tretyakov	open space
France	ONF (French Forest Board)	stainless steel and anodized aluminium	1	no		open space
Germany	Landesamt für Umwelt- und Arbeitsschutz	stainless steel	1	no		clearing
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft	galv. iron	25	no		various land use surroundings
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft	galv. iron	2	no		
Germany	LANUV NRW	aluminum	1	no		open space and forest
Germany	Northwest German Forest Research Station	galv. Iron, teflon	1	no		open space
Germany	Northwest German Forest Research Station	galv. Iron, teflon	1	no		open space
Germany	Northwest German Forest Research Station	Plexiglas, polyethylene	1	no		open space
Germany	Brandenburg LFE	Stainless steel aluminium, anodized	1	no		
Germany	Landesforstanstalt M-V	aluminum	1.1	no		open space
Germany	Thüringer Landesanstalt f. Wald, Jagd und Fischerei (TLWJF)	outer material stainless steel; inner bucket: plastic	1	no		clearing
Germany	FVA-Freiburg		1	no		
Germany	FVA-Freiburg	PE	27	no		
Germany	Bavarian State Insitute of Forestry	galv. iron	1.5	no		open field
Great Britain	FOREST RESEARCH	plastic	0	no		open space
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)	Funnel Copper, Body Corrosion Resistant Materials	1	no		variable
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)	Funnel Stainless Steel, Body Aluminum	1	no		variable
Latvia	Latvian State Forestry Research Institute "Silava"	plastic	1.5	no		open space
Slovakia	National Forest Centre	one plot - 2 m above canopy layer	1.5	no		

Table 10c: Evaluation of FutMon literature study questionnaire

Country	Institution	Distance to Next Obstacle	Obstacle Height	Precipitation Correction	Correction Method	Additional Wind Speed Measurements	Additional Temperature Measurements
Austria	Federal Research and Training Centre for Forests, Natural Hazards and Landscape	The distance to the next obstacle and the height of the obstacle depend on the site		yes	manual correction	yes	yes
Belgium	Research Institute for Nature and Forest (INBO)			no		yes	yes
Republic	Forestry and Game Management Institute	50	15-20	no		yes	yes
Denmark	Forest and Landscape Denmark, University of Copenhagen	measurements in a distance of 3 times the height of the nearest forest trees		no		yes	yes
Estonia	Centre of Forest Protection and Silviculture	200	25	yes	+0.2 mm for each measurement	yes	yes
France	ONF (French Forest Board)		variable, but the obstacles are at minimum at a distance of 2 times their height	no	weekly sums are compared with weekly observations made with a	yes	yes
Germany	Landesamt für Umwelt- und Arbeitsschutz	18	20	no		yes	yes
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft	50	15	yes	only data gaps UDATA	yes	yes
Germany	Forschungsanstalt für Waldökologie & Forstwirtschaft			yes	only data gaps UDATA	yes	yes
Germany	LANUV NRW	8	5	no		yes	yes
Germany	Northwest German Forest Research Station			no		yes	yes
Germany	Northwest German Forest Research Station			no		yes	yes
Germany	Northwest German Forest Research Station			no		yes	yes
Germany	Brandenburg LFE	31, 48, 14, 23	15, 17, 9, 12	no		yes	yes
Germany	Landesforstanstalt M-V	10	10	yes		yes	yes
Germany	Thüringer Landesanstalt f. Wald, Jagd und Fischerei (TLWJF)	5	2	no		yes	yes
Germany	FVA-Freiburg			no			
Germany	FVA-Freiburg			no		yes	yes
Germany	Bavarian State Insitute of Forestry	variable		yes	according to Richter 1995 method	yes	yes
Great Britain	FOREST RESEARCH	30		yes		yes	yes
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)			yes		yes	yes
Italy	Centro di Ricerca per lo Studio delle Relazioni tra Piante e Suolo (CRA-RPS)			yes		yes	yes
Latvia	Latvian State Forestry Research Institute "Silava"	100	9	no		yes	yes
Slovakia	National Forest Centre	min. 20m		no		yes	yes

Table 11 (Sevruk 2004): wind induced correction factor k for rain and snow for the Hellmann gauge

	u_{hp} in [m s^{-1}]							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
$N'_{0,3}$	k- values for rain (linear interpolation possible)							
20	1.010	1.015	1.020	1.015	1.020	1.030	1.035	1.040
30	1.010	1.015	1.015	1.020	1.025	1.035	1.040	1.050
40	1.010	1.015	1.015	1.025	1.030	1.040	1.050	1.060
50	1.010	1.020	1.025	1.040	1.045	1.055	1.065	1.075
60	1.010	1.020	1.030	1.040	1.050	1.060	1.070	1.080
70	1.010	1.020	1.030	1.045	1.055	1.065	1.075	1.085
80	1.011	1.026	1.031	1.046	1.056	1.071	1.081	1.091
90	1.011	1.026	1.036	1.051	1.061	1.081	1.086	1.096
100	1.011	1.026	1.036	1.051	1.061	1.086	1.091	1.101
Q	k- values for rain and snow air temperature during snowfall t= 0 to -8 °C							
5%	1.015	1.025	1.035	1.050	1.065	1.080	1.095	1.110
10%	1.015	1.030	1.045	1.065	1.085	1.100	1.120	1.145
15%	1.020	1.035	1.055	1.080	1.105	1.125	1.150	1.175
20%	1.020	1.045	1.065	1.090	1.120	1.150	1.180	1.215
25%	1.025	1.050	1.075	1.105	1.140	1.175	1.210	1.250
30%	1.025	1.055	1.085	1.120	1.160	1.200	1.240	1.285
35%	1.030	1.065	1.095	1.135	1.180	1.220	1.270	1.320
40%	1.030	1.070	1.110	1.150	1.195	1.240	1.295	1.350
45%	1.030	1.075	1.120	1.165	1.205	1.265	1.320	1.380
50%	1.035	1.085	1.130	1.180	1.225	1.290	1.350	1.410
55%	1.035	1.090	1.140	1.195	1.245	1.315	1.375	1.440
60%	1.040	1.095	1.150	1.205	1.270	1.335	1.400	1.470
65%	1.040	1.100	1.160	1.220	1.290	1.360	1.430	1.500
70%	1.045	1.110	1.170	1.235	1.310	1.385	1.460	1.530
75%	1.045	1.115	1.180	1.250	1.330	1.405	1.480	1.560
80%	1.050	1.120	1.190	1.265	1.345	1.425	1.510	1.590
85%	1.050	1.130	1.200	1.280	1.365	1.445	1.540	1.620
90%	1.055	1.135	1.210	1.295	1.385	1.470	1.570	1.650
95%	1.055	1.140	1.220	1.310	1.405	1.495	1.595	1.685
100%	1.060	1.145	1.230	1.320	1.420	1.520	1.620	1.720