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Investigation of short duration intensive rainfalls based on historical and recent data

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1. BACKGROUND AND OBJECTIVES OF THE RESEARCH

A peculiar duality is that water, which is an essential element for the existence of the individual and society, can at the same time be a source of many dangers and harms. Along providing access to water for the people and agriculture and industry, the protection against rainfall of goods, engineering facilities, equipment, resources, or the built or natural environment that provides production has been an ongoing task for humanity throughout its history.

Precipitation can damage the human environment in various ways, so by flooding goods, they can destroy their material and structure, thereby damaging or destroying the results of production or the equipment and infrastructure used for production.

One of the biggest threats to property and drainage systems is short duration heavy rainfall. The study of this phenomenon has been the subject of numerous researches worldwide since the last quarter of the 1800s. The dissertation deals with intense heavy precipitation, its measurement, and correction of certain errors related to the measurements; beyond the correction procedure, their effect on precipitation intensity curves is also in the focus of the study.

The short duration heavy rainfall can cause damages beyond the field of engineering (water engineering); their effect is also relevant from an environmental and agricultural point of view. This research on the topic can primarily be helpful for engineers to plan the prevention of water damages. The relevance of the topic in agriculture is reflected not only in runoff-related erosion phenomena but also in the issue of drop erosion. During heavy rainfall, larger-diameter drops fall, effectively destroying the soil particles' structure due to the force of their impact, and then the water transports the soil. The result of the drop-caused soil erosion, the surface is transformed rapidly by the transported soil and causing sediment accumulation parallelly in other places. Both erosion and alluvial deposition cause damage to the natural, agricultural or urban environment.

Research on the topic has also come to the fore due to global warming and climate change. In recent years, it has become a common belief that the Intensity-Duration-Frequency (IDF) curves used to dimension drainage systems have become obsolete as precipitation has changed and precipitation has become more intense as one of the effects of climate change. One of the commonly recurring elements of climate projections is that even the highest intensities of domestic rainfall will increase in the decades ahead, similar as in much of the world. Numerous publications report an increase in the annual maximum of the maximum daily precipitation. Several climate change projections derived from climate models show a higher frequency of short-duration heavy precipitation and increased rainfall intensities. Reference data are necessary for the preparation of this segment of climate projections. These are also crucial for examining the changes estimated based on the projections. The reference data are necessarily precipitation data measured in the past and present, so these must be as accurate as possible.

It is worth distinguishing between historical and current data among the reference data, mainly due to the differences in measurement, data recording and storage method, and data processing. In the dissertation, the term historical data refers to the data collected by analogue measuring instruments, stored in tabular form, typically in abstracts, concerning the highest values, and the data recorded with an extended measurement period in the first period of digital measurement. The term recent data includes precipitation data measured recently, typically recorded with a one-minute measurement period, or digitized in this way.

Since the initials of the precipitation measurements, there are several uncertainties regarding the accuracy issues, which also affects the reliability of precipitation data and the rainfall intensity data. Without sufficiently accurate rainfall data, it is difficult to form a well-based opinion about the change in precipitation conditions, which in itself justifies increasing the accuracy of current measurements and re-checking, correcting as much as possible and reprocessing historical precipitation data.

The backbone of the measurements over the last one and a half hundred years has been based on the principle of weight or volume measurement. In the dissertation, I examined two commonly used volume measurement-based methods in Hungarian practice, so there were in the focus of the research the error sources of the siphoned level measurement rainfall recorder (SRW) and the tipping bucket rainfall gauge (TBG).

Errors in rainfall intensity data can be divided into three major groups. In the first, there are inaccuracies caused by the external conditions of the measurement (mainly the effect of wind). The rainfall measurement devices have systematic errors, these depend on the measurement techniques, and these are unique to every measurement tool. The third group of errors occur during the data processing.

The dissertation deals with all three error classes, focusing primarily on the individual systematic errors and their subsequent correction for historical data.

Correction of precipitation data also affects the IDF curves In the dissertation, the effect of the corrections is investigated on the historical data of the Budapest Belterület rain gauge measured with the Hellmann-Fuess rainfall recorder and the Lambrecht type tipping bucket gauge.

1.2. THE AIM OF THE RESEARCH

The objectives of the research summarized in the dissertation were as follows:

A. Measurement errors in the application of SRW gauges and their effect on the measurement of precipitation intensity, development of a method for the correction of systematic measurement error in the processed historical precipitation data. Many types of siphon rain gauges were used worldwide, as well in Hungary. The World Meteorological Organization (WMO) has organized measurement campaigns to investigate the accuracy issues of traditional rain gauges and rainfall intensity measurement devices, to clarify the accuracy categories and correction functions to fix the measurement errors. First of all, TBG tools have been tested in this round; meanwhile, SRW equipment has not yet been inspected. The research aims to define the measurement errors of the devices operating on the principle of level measurement (losses due to undercatch caused by wind, splashes, evaporation, wetting, etc.) and to estimate their effect in determining the precipitation intensity. The most important systematic error of SRW gauges resulted from the paused measurement while emptying the measuring tank. If the registration ribbon is available, the correction can be performed based on the procedure proposed by Luyckx and Berlamont. However, a significant part of the historical data can only be found in abstract form, so the said method cannot be applied to fix them. For this kind of data, a new procedure must be developed.

B. Investigation of the accuracy issue related to the correction of systematic error of TBG devices; development of an additional correction procedure. Historical precipitation data measured with TBG devices were usually recorded with a measurement period of several minutes (typically 10 minutes). Correction formulas have been developed for instruments in recent years, but these can only be applied to one-minute data. These procedures cannot be used directly for data aggregated over more extended periods due to the nonlinear nature of the correction formulas, so an additional correction is required.

C. Demonstration of the effect of data processing errors in historical precipitation data. Precipitation intensity was measured only recently with a one-minute measurement period; prior 10 minutes or more extended period's rainfall depth was registered. Since the beginning of the rainfall and the measurement period do not necessarily coincide, the highest measurable rain depth or intensity can be registered. This error has a magnitude that can also affect the IDF curves, so the error is undoubtedly present in the presently used IDF curves. It is necessary to examine the nature and range of this error. Another issue is the error of approximation of IDF curves by some analytic formulas, e.g. power functions. The research goal is to study these phenomena and estimate their effects in the context of IDF curves.

D. Correction of rainfall intensity data of the Budapest Belterület gauge with the developed procedures, examining the effect of the correction in the precipitation maximum curves (case study). The rainfall data of the gauge have been measured through an SRW and a TBG rain gauges. The data show the issues presented in the A and B points, so a correction procedure was needed. After performing the correction, its effect can be examined on the historical precipitation data set. Based on the examination, the magnitude of the correction can be determined. Other factors that affect the accuracy of the measured data may be considered, such as bias in power function based IDF curves used for practical purposes, compared to the data calculated by the probability theory and statistics.

2. METHOD AND MATERIAL

Investigating the measurement errors of SRW devices, I started using the concept of Sevruk, who had been examining the sources of measurement errors of traditional rain gauges in 1982 and has been evaluating the procedures used for corrections. This approach was made possible because of many elements or conditions of measurement, and therefore the nature of the errors are the same or very similar for conventional gauges and SRW rainfall recorders.

I also examined the issue of the inaccuracy of SRW meters due to the effect of wind, tracing them back to the research and results of traditional meters. In the course of the study, by comparing the flow conditions around the conventional and SRW equipment, I sought an answer to the extent to which the measurement error of the two types of meters due to wind may differ. In 1999 and 2000, Nešpor et al. and Habib et al. performed flow studies on conventional Hellmann rain gauges. Using SimFlow software, a numerical model of the conventional gauge and the SRW made it possible to compare the magnitude of the current around the two devices, thus estimating the expected measurement error for the SRW device compared to the conventional gauge, checking the results comparing them to the results of the before mentioned researchers.

The most significant systematic error of SRW devices is caused by the pause of registration of water level in the measurement tank of the device during the emptying of the gauge. However, the intensity of precipitation can be inferred from the duration of the discharge. If it rains during the discharge, the discharge phase is more extended, related to the intensity of the precipitation. Based on this consideration, Luyckx and Berlamont have developed a procedure to perform a correction, reading the time and instantaneous rainfall intensity from the registration ribbon. This method is not suitable for the correction of extracted data, where only the average intensity is known with the referring time period, but using an appropriate consideration, the number of siphonages can be estimated from the registered precipitation amounts, and so the unmeasured rainfall amount can be determined, and the precipitation intensity can be corrected.

For TBG devices, the most significant systematic error occurs during emptying of the tipping bucket. During 2004-2009, Vuerich et al. and Lanza et al. performed laboratory and field measurements and intercomparisons on several instruments on behalf of WMO. During their research, the correction parameters for several products were determined for a power function correction formula. Their procedure was based on a one-minute data collection period because this measurement frequency is currently used in the measurements. To correct data collected from historical TBG data where a more extended measurement period was used, this formula cannot give an accurate result due to the nonlinearity of the correction formula. The correction formula can be improved by an additional correction formula derived from mathematical and statistical considerations.

To determine the effect of the SRW and TBG corrections, the precipitation intensity data of the Budapest Belterület gauge were examined. After the corrections, IDF curves were generated using the necessary statistical analyzes.

Those precipitation data which were registered with a constant measurement period cause underestimation during data processing. A comparative study can be performed on one-minute data to estimate the degree of bias. Simulated measurement time series realizations can be performed with a time series registered with a one-minute sampling period by shifting the starting time of the measurement. The different measurement realizations result in different rainfall intensities, where the maximum value of the one-minute time series can be approached; in most cases, only one series can reproduce it. In reality, only one time series realization can be measured during the measurement, and this one can be any of the realization, namely with equal probability. In the simulation, therefore, it can be assumed that the value of the "maximum" in the time series will be in the vicinity of the average of the largest and smallest maxima of the realizations. The distance of the average of the obtained maxima and the highest one is also an estimate of the rate of the under-measurement.

IDF curves are not analytical functions; these are data sets produced using probability theory and statistical analysis. At the end of their production, in many cases, in order of simplified application - in Hungarian practice - it is customary to approach it with a power function. The error resulting from the approximation can be made by comparing the IDF values calculated on a probabilistic basis with the approximation function.

The theoretical results were achieved during the research during the processing (correction) of the data provided by OMSZ, and thus it was possible to draw the conclusion. The data were collected at the Budapest Belterület meteorological station between 1915 and 2018.

The data were collected in the 1915-1992 period through a Hellmann-Fuess type SRW device, while a Lambrecht 15188 type TBG gauge registered the 1998-2018 period data.

In my study, I used a time series of an extreme rainfall detected in Germany, Abtsgmünd-Untergröningen rainfall gauge, on 11 July 2018. These data series were downloaded from the open database of the German Meteorological Service (Deutsche Wetterdienst).

An additional source of data for the research was the calibration data and the technical characteristics of the instruments. I cited the sources in the dissertation.

The inhomogeneity of the precipitation data could be expected. There were several reasons for this, such as the fact that the data did not form a continuous data series, data for many years were missing, the environment of rain gauges was built with 4-5 storey buildings from the 1930s and the location of gauges changed. Homogeneity testing was performed using the Pettitt, Neumann, and Kruskal Wallis H tests. The first two tests allowed the examination of the complete data set. At the same time, the third was suitable for a comparative analysis of the data of four subperiods divided due to data gaps and different measurement conditions.

3. RESULTS

3.1. THESES

1. I proved that the power function correction of tipping bucket precipitators determined in a short measurement period should be used for instruments with a power factor value exceeding 1.10. In this case, the rate of the additional correction is higher than 2%.

2. I have developed a procedure to improve the historical data of siphoned rainfall writers to decrease systematic measurement error due to siphoning, for cases where only average precipitation intensities and their duration can be used, and the registration ribbon is no longer available.

3. I verified that for the multi-minute sampling period data series, the probability of obtaining the absolute one-minute series maximum is the reciprocal of the time measured in minutes.

4. In the time series measured by a continuous 10-minute sampling period, there can be a 3-7% underestimation in the highest rainfall intensities due to the regularities of sampling.

5. I verified through a numerical aerodynamic analysis that the Hellmann rainfall writer induces more significant deformation in wind speed distribution, so the wind-caused rainfall measurement error can also be higher than in the case of the traditional Hellmann rain gauge, assuming that there was not a windshield applied during the measurement.

6. I verified that the yearly maximum rainfall intensity data of the Budapest Belterület rainfall gauge were homogeneous and identically distributed after the correction of the systematic errors of rainfall intensity data measured through SRW and TBG devices.

7. Based on the data of the highest annual rainfall intensity of the Budapest Belterület rainfall gauge, I showed that the measurements with SRW and TBG instruments in the 10 minutes duration are 5-8% higher, and in 20 and 30 minutes duration are 2-6% higher compared to uncorrected values.

3.2. NEW SCIENTIFIC RESULTS

Post-correction of the processed data of the SRW gauges to correct the siphoning error.

In the course of the research, I developed a method to correct the error of SRW rainfall recorders' processed data due to the measurement tank's emptying error. The method is suitable for the correction of the error resulting in under-measurement. The advantage of this procedure is that it can eliminate the underestimation even from the data that can only be found in the extracted form. Since this kind of underestimation is proportional to the rainfall intensity, the higher rainfall intensities contain higher error, which propagates into the IDF curves. With the fixed data, a more confident picture can be obtained about the extreme rainfall intensities. The method was prepared in a generalized, parametric form, so it is suitable for the data measured by rainfall recorders if the technical parameters of the SRW device are known. As these devices have been used worldwide to gain rainfall data for a significant part of the last century, improving the data can be an important issue beyond the borders of Hungary.

In Hungary, Hellmann-Fuess rainfall recorders were typically used, so I corrected the precipitation data received from the National Meteorological Service based on the rainfall recorder's parameters. The results of the test are shown in Table 1.

Table 1. Highest values of the correction factor for Hellmann-Fuess rainfall writer's rainfall intensity data, by the 5, 10, 20, 30, 60 minutes measurement intervals

Frequency in years	5 minutes	10 minutes	20 minutes	30 minutes	60 minutes
1 year	1,00	1,00	1,00	1,01	1,01
2 years	1,06	1,03	1,02	1,03	1,03
10 years	1,06	1,06	1,05	1,05	1,05
100 years	1,21	1,13	1,10	1,13	1,13

Based on the correction factors, I found that the correction shows to be significant over the ten-year average time of return, so in the case of extreme rainfalls, the correction is higher than 5%. For the data of 100 years average recurrence, the correction was 10-13%.

Supplementary correction for the TBG devices for data collected (or stored) in a multi minutes sampling period

In the research, I developed a supplementary correction of the data measured by TBG devices in a multiminutes sampling period to correctly use the earlier applied power function-based formula, proposed after the WMO intercomparison campaign in 2009.

The systematic error of TBG meters consists of the loss due to the splashing of water collected in the measuring spoon, the amount of unmeasured precipitation that drains during the emptying of the spoon, first of all. A power function is often used in the literature to correct the error; therefore, the correction is nonlinear. The correction can be applied adequately to that sampling period of data on which it was developed. If the raw data were registered in a different sampling period, the correction will not be correct due to nonlinearity, and an underestimation remains in the data. If such measurements need to be corrected, the power function correction can only be applied with an additional correction. In my research, I derived an additional correction factor and examined its range and the limitations of its application. For practical use, a general characteristic value of the correction factor must be determined based on statistical analysis since there are no one-minute data available in practical cases. This general characteristic value can be determined from one-minute rainfall data for a geographic region.

The additional correction is recommended for those rainfall recorders, which can be characterized as a significant systematic error in the range of high intensities, and therefore the exponent of the one-minute correction relationship is around 1.10 or greater. In the case of a smaller exponent, the application of the supplementary correction has significance only in the case of long sampling periods. As the UN World Meteorological Organization recommends that measurements continue to be reported in ten-minute data in many cases, the correction may also be relevant to the correction of current measurements.

The developed method can be applied to any measurements, not exclusively for meteorological ones, where a power function formula-based correction formula has to be used to correct data in the circumstances mentioned above.

3.3. FURTHER SCIENTIFIC RESULTS

There is not seeming significant change in the rainfall intensity data of the Budapest Belterület rainfall gauge data.

During the examination of the rainfall gauge data, I examined the uniformity of the individual subperiods. In connection with this, I found the mean and extreme values of the sub-data series trendless. All this suggests that the 100-year data for this meteorological station show no change in the maximum annual rainfall intensity. The lack of trend in the data of this station contradicts the often generally asseverated statement that the maximum precipitation intensities increase due to climate change, also in Budapest. The geographical location of the station may explain the lack of a significant trend. A possible explanation can be that Budapest is relatively far from the seas, and most of the rain falls from the wet air on the around thousand-kilometre road that reaches the surroundings of Budapest, mainly from the Mediterranean region. The moist air coming here can, of course, cause significant thunderstorms as also before, but there is no longer any change in the durability of extreme high intensities within the thunderstorm. This assumption could be confirmed or refuted by analyzing historical precipitation intensity data from rainfall gauges along the usual Mediterranean air masses route. This result may therefore be the subject of further research.

Nevertheless, this result does not contradict the ascertainment of domestic climate research, which show a decrease in the number of rainy days and, in parallel, an increase in the average daily rainfall intensity on rainy days. It can be seen that the average intensity for rainy days does not provide information on changes in the highest possible or infrequently occurring peak intensities with a low probability of exceedance.

IDF curves generated from rainfall data measured with 10 minutes sampling period may contain an underestimation with a mean of 3-7% for 10-30-minute durations due to data processing.

The long sampling period rainfall data cannot describe accurately those fluctuations which occur in a shorter time than the sampling period. This property is similar to those proven by the sampling theorem of Shannon and Nyquist, developed for the sampling of periodic signals. Although the time series of precipitation intensity observed during rainfall is aperiodic, biases similar to the approximation problems of periodic functions can be observed in this situation.

If the precipitation (precipitation intensity) is assumed to be a quantized signal sequence in minutes, then a measurement period of n minutes can be measured in n-ways. Suppose a rainfall is sampled using 10 minutes sampling period. In that case, ten independent time series can be generated (supposing that the time series were measured in identical minutes), so ten types of measurements can be realized. Different possible realizations provide different maximum values, of which the absolute maximum can generally be reached only in one of the realizations. The latter circumstance ensures that the measured maxima will be less than the actual maximum in most cases. The error range was examined over the time series of an extreme precipitation, and the extreme values are shown in Table 2. The table data were gained from the 11 July 2018 rainfall, measured in Abtsgmünd-Untergröningen, Germany.

Table 2. Highest and lowest rainfall intensities in the case of different sampling periods

Sampling Period	Interval	Min. intensity	Max. intensity	Min/Max range
5 minutes	5	123.12	128.64	4%
	10	119.46	123.06	3%
	20	105.09	110.94	5%
	30	85.02	86.78	2%
	60	48.77	48.84	0%
10 minutes	10	110.58	123.06	**10%**
	20	94.83	110.94	**15%**
	30	80.90	86.78	**7%**
	60	48.47	48.84	**1%**
20 minutes	20	69.03	110.94	38%
	60	47.26	48.84	3%
30 minutes	20	69.03	110.94	38%
	60	47.26	48.84	3%

As Table 2 shows, the maximum and minimum values rate range is 7-15%. Assuming that the mean value of the deviations is the arithmetic mean, in the case of the 10-minute measurement period, the deviation is in the 3-7% band below the actual minute maximum, i.e. it contains an underestimation. This error propagates into the IDF curves.

It can be seen that the degree of deviation depends on the fluctuation of the change in intensity, so in the case of less variable precipitation, the underestimation is smaller. At the same time, extreme precipitation is characterized by a significant change in intensity.

4. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions and recommendations based on the dissertation are the following.

Due to inaccuracies in the measurement of precipitation intensity, a significant error can be made in the IDF data that is relevant to practical use. The errors can be classified into three types, partly identical to the conditions of traditional precipitation measurement, partly due to the structural design and technique of the rainfall recorders, and partly due to the data processing methods.

Errors in the determination of rainfall intensity due to the measurement conditions, similar to conventional rain gauges, can be traced primarily to the disturbing effect of the wind. Elimination or subsequent error correction is still unresolved for sub-daily or more detailed rainfall and rainfall intensity data. The solution to this issue will be achieved by aerodynamic modelling of the measurement process of the gauges and by parallel wind and rainfall measurements or by statistical examination of the conditional occurrence of wind and precipitation.

Systematic errors of rainfall intensity measurement depend on the measuring equipment, so their correction can be ensured more easily. Research relating to some important parts of this topic has been already taking place. In the dissertation, I developed procedures for the post-correction of previously documented measurements for both SRW and TBG instruments. A significant 5-10% increase can also be observed in the adjusted precipitation intensity data, especially in the range of extreme intensities.

Long sampling period measurements can also lead to uncertainties in the databases, resulting in underestimation. Estimating the uncertainty by averaging the minimum and maximum values for the 10-min measurement period, an under-measurement of 3-7% can be detected for short 10-30-minute durations.

Errors can be added by type in the cases of measurement using SRW or TBG devices. For the SRW instrument, the systematic error may be added to the wind caused error, and for the TBG device, the systematic error may be added to the wind error and the long sampling period caused error of historical data.

The detected errors propagate into the IDF data, so their correction should be necessary. Improving IDF data can have an impact in two important areas. By adjusting the climate data reference, a more accurate picture of the range of change can be obtained; and regarding the expected capacity of the previously built drainage infrastructure, a reassessment can be done for a more precise definition of development needs.

Based on the result of the research, I formed the following recommendations.

A. The analysis of the wind caused error in the historical data is essential. The examination of sub-daily wind and rainfall data is necessary to determine the joint statistics of precipitation and wind; it can be a basis for a statistical correction of historical rainfall data.
B. To detect the wind-caused inaccuracy, aerodynamic modelling of previously used rainfall recorders is needed; it is essential to estimate the wind-induced error in rainfall measurement.
C. It is necessary to cleanse early precipitation data from systematic errors; in this way, historical data can be revised, and thus historical climate data can be corrected.

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