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Technical description of the KNMI Rainfall Generators for the Rhine and Meuse basins

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1. Introduction

This report gives a technical description of what is briefly known as the KNMI Rainfall (or Weather) Generators for the Rhine and Meuse basins. These rainfall generators form part of the GRADE system for respectively the rivers Rhine and Meuse. GRADE stands for Generator of Rainfall and Discharge Extremes and is a collective development of Rijkswaterstaat, Deltares and KNMI. The KNMI rainfall generators are not single programs but are sets of programs that altogether form what we call ‘the rainfall generators’. They contain programs that are considered as the core of the rainfall generators (and that are essentially the same for both rainfall generators) but also programs for pre-processing the historical meteorological data that serve as basis for the weather generators and programs for post-processing the synthetic data produced by the weather generators. This report describes all these programs and the steps that are needed to run these programs to generate the (current) reference Rainfall Generator (RG) simulations for the Rhine and Meuse basins, to perform an uncertainty analysis for both Rainfall Generators, to convert the Rainfall Generator output to the data-format suitable for the GRADE-FEWS¹ system, and to update the Rainfall Generators in the future by incorporating more recent historical meteorological data.

Most of the information in this report was already published; in KNMI Publications 186-I to 186-VII for the RG for the Rhine basin and in Publications 196-I to 196-VI for the RG for the Meuse basin. While these reports present the Rainfall Generator developments in historical order this report gives a systematic overview of the components of the latest versions of the Rainfall Generators and of the similarities and differences between them. The focus in this report is thus on the application and

¹ GRADE-FEWS: The Flood Early Warning System (FEWS) developed by Deltares that is used within GRADE to couple the Rainfall Generator, and the hydrological - and hydrodynamical models and which also includes post-processing of river discharge data.

the updating (in the future) of the Rainfall Generators. In this respect it can also be regarded as an application manual of the KNMI Rainfall Generators.

An important goal of this report is therefore to give sufficient details (together with references to earlier work) about how to reproduce the current Rainfall Generator results and how to produce updated Rainfall Generator results in the future. This document describes the status of the Rainfall Generators at the end of 2013/early 2014. These are the Rainfall Generators that were used to generate the 50,000-year reference simulations for the Rhine and the Meuse basins which are used in the version of GRADE (version 2.0) provided to WTI2017² in 2014, and of which the results are described in detail in the GRADE Final Report (Hegnauer et al., 2014).

2. Pre-processing of precipitation and temperature data

a. RG for the Rhine basin

Pre-processing of the historical precipitation and temperature data involved only interpolation of the E-OBS (v7.0) precipitation and temperature data and the HYRAS (v2.0) precipitation data for the period 1951-2006 to 134 HBV-Rhine sub-basins. For this the original E-OBS and HYRAS grids are first ‘interpolated’ to a fine 2.5 km × 2.5 km grid using Thiessen-interpolation³. This fine grid is then aggregated to the HBV sub-basins. The programs used for the precipitation and temperature pre-processing are described in step 1 in Appendix A: Workflow of the GRADE Rainfall Generators.

For future updates of the RG for the Rhine basin using an extended base period pre-processing of historical data will only involve interpolation of the extended (and updated) E-OBS precipitation and temperature data to the 134 sub-basins. For further steps involved in the update of RG Rhine see Section “How to update the RGs for the Rhine and the Meuse with an extended base period (post-WTI2017)”.

b. RG for the Meuse basin

Pre-processing of the historical precipitation and temperature data for the Meuse basin involved much more steps than that for the Rhine basin. Basically the reason is that no sufficiently detailed gridded historical data sets are available for the Meuse basin and that there is no coordinated action for producing such datasets as from The International Commission for the Hydrology of the Rhine basin (CHR). Therefore unlike the weather generator for the Rhine basin, the simulations for the Meuse basin are driven by station data which have been obtained (i.e. bought) from Météo France and Royal Meteorological Institute of Belgium (RMIB). The used German station data (station Aachen) are publicly available from Deutscher Wetterdienst (DWD).

To drive the RG Meuse simulations daily sequences of seven precipitation and two temperature stations are used for the period 1930 – 2008, (but without 1940 – 1945). The precipitation stations are: Chaumont, Nancy, Vouziers, St. Quentin in France, Chiny-Lacuisine and Uccle in Belgium and Aachen in Germany; and the temperature

² WTI in WTI2017 is a Dutch abbreviation (for Wettelijk Toetsings Instrumentarium) that is used by Rijkswaterstaat for determining the official dike heights.

³ In this method each 2.5 km × 2.5 km grid cell simply receives the value of the nearest E-OBS or HYRAS grid cell.

stations: Uccle and Aachen. The precipitation stations were selected after a homogeneity analysis of the records for the period 1930 – 1998 (Leander and Buishand, 2004a). A homogeneity analysis of these stations for the complete 1930 – 2008 period gave rise to an adjustment of the precipitation series of Chaumont and Vouziers (Buishand and Leander, 2011). Further details about the pre-processing of these data are given in Leander and Buishand (2004b) for the base period until 1998 and in Buishand and Leander (2011) for the 1999 – 2008 part of the full base period.

For coupling with the hydrological model, the daily average precipitation for 15 HBV-Meuse sub-basins for the period 1961 – 2007 was constructed, partly from station data and partly from area-average rainfall data. For the French part of the Meuse basin the sub-basin average precipitation was based on interpolation of the daily data from 55 to 63 stations to a 2.5 km × 2.5 km grid by inverse squared distance weighting. For the Belgian part of the Meuse basin the HBV sub-basin average precipitation was derived from the daily average precipitation for 31 (RMIB) sub-basins that was routinely calculated by RMIB⁴. Daily average temperatures for the 15 HBV sub-basins were calculated from inverse squared distance interpolation of daily temperature data from eleven stations for the period 1967 – 2008. Details of the calculation of the area-average daily precipitation and temperature for the 15 HBV-Meuse sub-basins are given in Buishand and Leander (2011).

The different historical periods of the meteorological data used for the 50,000-year reference simulations for the Rhine and Meuse basins are summarized in Table 1 (under Historical/reference data).

For future updates of the RG for the Meuse basin (i.e. extending the base period) either the procedure to extend the base period described in Buishand and Leander (2011) can be followed or the resampling can be driven by an extended version of the E-OBS dataset as for the RG for the Rhine. These procedures are described in more detail in Section “How to update the RGs for the Rhine and the Meuse with an extended base period (post-WTI2017)”.

3. Fortran sub-programs that compose the core of the RGs

There are three Fortran sub-programs that compose the core of the RGs for the Rhine and the Meuse basins. Two of these three programs are essentially the same for the Rhine and Meuse basin. For the two similar programs the differences are limited to differences in geographical area (determined by the input data) and the different composition of the feature vector (FV), see also Table 1. The third program contains for the Meuse basin an extra (resampling) step.

The three sub-programs are `FVECTORS.F`, `RESAMPLE.F` and `BACKTRAN.F`. After the pre-processing of the historical precipitation and temperature data, `FVECTORS.F` produces the feature vector elements for the (selected) historical base period, which are subsequently used as input for `RESAMPLE.F`. The program `RESAMPLE.F` does the actual nearest neighbour resampling and essentially produces a list of simulated historical dates for the desired number of simulated years (i.e. 50,000 years for the reference simulations and 20,000 years for the simulations in the

⁴ In 2007 RMIB stopped with the routinely calculation of sub-basin average precipitation.

uncertainty analysis of the RG). In addition to the historical date RESAMPLE.F provides for each simulated day the (randomly) simulated rank j (i.e. a value between 1 and k); where k is the number of selected nearest neighbours so that in any case a particular simulation can be reproduced (even if on a different computer the built-in random number generator would generate a different random number sequence). Based on the simulated sequence of historical dates (in the index-file produced by RESAMPLE.F) program BACKTRAN.F generates the actual sequence of precipitation and temperature for each sub-basin (134 for the Rhine and 15 for the Meuse). For the Meuse basin BACKTRAN.F makes use of a second resampling step to account for the fact that the sub-basin precipitation and temperature data (ultimately used for the coupling with HBV) covers a shorter historical period than the station data used for driving the resampling procedure (see also Table 1: Historical/reference data, and for details see Buishand and Leander, 2011). BACKTRAN.F also rescales the standardized historical data to the scale that corresponds to the calendar day in the simulation. Note that for the historical base period each calendar year (including leap years) consists of 365 days. To achieve this, during leap years the 31st of July is excluded, while the 29th of February is kept. The reason for this is that the winter half-year is considered the more important season and that with this choice no historical data from this season is removed. A more technical description of the main Fortran sub-programs is given in Appendix B: Main Fortran sub-programs. This description can also be found under: <http://www.knmi.nl/~beersma/nnres/>. These three programs are also part of step 2 in Appendix A: Workflow of the GRADE Rainfall Generators, where they are combined in the (shell) script `run_resample*.sh`.

4. Post-processing of the RG simulations

Conversion from Julian to Gregorian calendar

Originally the RGs for the Rhine and Meuse basins made use of the Julian calendar (each fourth year is a leap year). But the FEWS-GRADE system, which uses the RG simulations as input, makes use of the Gregorian calendar in which each year that can be divided by 100 but not by 400 is not a leap year anymore (this system of leap years, with an average of 365.2425 days, is much closer to the solar year of 365.2422 days than the 365.25-day year in the Julian calendar). The original RG time series (with the Julian calendar) are adapted to the Gregorian calendar by deleting the leap days of the simulated years 100, 200, 300, 500, 600, 700, 900 and so on. To avoid the major calendar correction in the year 1582 all simulations start in the year 2001 rather than in the year 1. A 50,000 year simulation therefore runs from the year 2001 to the year 52,000. This calendar conversion is done during the conversion of ASCII- to NetCDF files (see below or step 4 in Appendix A: Workflow of the GRADE Rainfall Generators).

Simulation of potential evaporation (PET) for the Meuse basin

For the Meuse basin, daily potential evapo(transpi)ration (PET) was calculated from a regression of daily PET on daily temperature (T). This regression relation has the

form (Leander and Buishand, 2007):

$$PET = [1 + \alpha_m (T - \bar{T}_m)] \overline{PET}_m \quad (1)$$

with \bar{T}_m the mean observed temperature ($^{\circ}\text{C}$) and \overline{PET}_m the mean observed PET (mm/day) for calendar month m . The coefficient α_m , and the averages \bar{T}_m and \overline{PET}_m were derived from daily temperature and PET data for the Belgian sub-basins for the period 1968-1989, which were made available by RMIB. The regression coefficient α_m (which is the same for all sub-basins) varies from $0.07 \text{ }^{\circ}\text{C}^{-1}$ in September and October to $0.18 \text{ }^{\circ}\text{C}^{-1}$ in February. These coefficients replaced the single value of α of $0.17 \text{ }^{\circ}\text{C}^{-1}$ determined earlier by van der Wal (2002). A Fortran program `pet2_for_NG_Maas.f` based on Equation (1) is used to simulate for all 15 sub-basins the daily PET from the daily temperature simulated by the RG for the Meuse basin. For the Belgian part of the basin \overline{PET}_m is derived from the daily evapotranspiration data obtained from RMIB and for the French sub-basins the average of the Belgian sub-basins is used, because of lack of suitable evapotranspiration data. Note that although the French sub-basins all use the same \overline{PET}_m , daily PET varies over the sub-basins because the daily temperature varies over the sub-basins. Daily PET is thus calculated (externally) as a post-processing step of the RG for the Meuse basin. The daily PET simulated this way is included in the NetCDF files of the RG for the Meuse basin (see below).

For the Rhine basin daily PET was calculated internally by HBV, i.e. the hydrological model within GRADE, and was therefore not included in the RG NetCDF files. In HBV-Rhine a similar PET-T relation was used. For the Rhine the \bar{T}_m and \overline{PET}_m values derived by Eberle et al. (2005) were used which are based on the years 1961-1995. Effectively, \bar{T}_m and \overline{PET}_m are parameters in HBV⁵ that vary over time and over the HBV sub-basins. However, for the Rhine basin the coefficient α_m ⁶ is constant and equals $0.05 \text{ }^{\circ}\text{C}^{-1}$ for all calendar months and all sub-basins.

Conversion of ASCII output to NetCDF

BACKTRAN.F produces ASCII files. For the interface with FEWS-GRADE these ASCII files are converted to NetCDF files. The NetCDF files consist of chunks of 2000 years⁷ so a 50,000 year simulation corresponds with 25 NetCDF files. The conversion to NetCDF makes use of the NetCDF Climate and Forecast (CF) Metadata Conventions Version 1.6, 5 December, 2011 (in short CF-1.6, see also <http://cf-pcmdi.llnl.gov/documents/cf-conventions/1.6/cf-conventions.html>). The metadata used and the general structure of the NetCDF files are given in Appendix C: Metadata and structure NetCDF files. The NetCDF files for the RG for the Rhine basin contain

⁵ In HBV-Rhine \bar{T}_m actually represents a long-term calendar day average rather than a long-term calendar month average (see e.g. G6rgeen et al., 2010, page 39).

⁶ In HBV the coefficient α_m is called the *etf* parameter.

⁷ Chunks of 2000 years were chosen since in the Gregorian calendar periods of 400 years contain always exactly 146097 days (400×365.2425). Therefore files containing 2000 years of data all have the same length while files containing e.g. 1000 years of data have varying lengths (i.e. one day more or one day less in subsequent periods).

the daily precipitation and temperature data of the RG simulation and the NetCDF files for the RG for the Meuse basin contain daily PET data as well.

The (Fortran) programs that actually produce the NetCDF files are called **ncGRaDE-Meuse3.f** and **ncGRaDE-Rhine3.f** and are used in combination with the (shell) scripts **run_ncGRaDE*.sh** as indicated in step 4 in Appendix A: Workflow of the GRADE Rainfall Generators.

Table 1: Summary of characteristics of simulations with the RGs for the Rhine and Meuse basins (resp. RG Rhine and RG Meuse).

Item	RG Rhine	RG Meuse
(short) name of reference simulation	nomem_gvar_50000_pass_hyras ¹⁾	mem4d_gvar_50000 ²⁾
Length of reference simulation (years)	50,000	50,000
Calendar	Gregorian (365.2425 days per year with ordinary Gregorian leap day exceptions); simulations start in the year 2001 to avoid the major calendar correction in the year 1582	Gregorian (365.2425 days per year with ordinary Gregorian leap day exceptions); simulations start in the year 2001 to avoid the major calendar correction in the year 1582
Date of reference simulation	November 2012	May 2013
Names of NetCDF files (2000 years each)	Rhine_2012_v01.1_reference_50K_part01.nc to Rhine_2012_v01.1_reference_50K_part25.nc See Appendix C	Meuse_2013_v01.1_mem4d_reference_50K_part01.nc to Meuse_2013_v01.1_mem4d_reference_50K_part25.nc See Appendix C
Meta data in NetCDF files		
Memory term included	No	Yes, 4-day precipitation sum (mem4d) ²⁾
Composition of feature vector	P, T, F ¹⁾ (P refers to precipitation, T to temperature and F to fraction of the area with precipitation)	$P, T, \text{mem4d}$ ²⁾
Weights of feature vector elements	2.33, 1.10, 6.38 ¹⁾	2.19, 1.05, 0.30 ²⁾
Value of k for Decreasing Kernel	10 ¹⁾	10 ²⁾
Moving window (days)	61 ¹⁾	121 ²⁾
Standardization of P and T	Yes ¹⁾	Yes ²⁾

Item	RG Rhine	RG Meuse
<i>Historical/reference data</i>		
<i>P</i> data used for ‘driving’ resampling procedure (i.e. data used in feature vector)	E-OBS v7.0 (1951-2006) interpolated to 134 HBV-Rhine sub-basins ¹⁾	7 precipitation stations (1930-2008 except 1940-1945) ²⁾
<i>T</i> data used for ‘driving’ resampling procedure (i.e. data used in feature vector)	E-OBS v7.0 (1951-2006) interpolated to 134 HBV-Rhine sub-basins ¹⁾	2 temperature stations (1930-2008 except 1940-1945) ²⁾
<i>P</i> data used for coupling with hydrological model	HYRAS v2.0 (1951-2006) interpolated to 134 HBV-Rhine sub-basins ¹⁾	Daily <i>P</i> (1961-2007) for 15 HBV-Meuse sub-basins ³⁾
<i>T</i> data used for coupling with hydrological model	E-OBS v7.0 (1951-2006) interpolated to 134 HBV-Rhine sub-basins ¹⁾ (same as <i>T</i> data used for ‘driving’ resampling procedure)	Daily <i>T</i> (1967-2008) for 15 HBV-Meuse sub-basins ³⁾
Passive simulation	Yes (HYRAS <i>P</i> passively simulated) ¹⁾	No
Second Nearest - Neighbour steps	No	Yes ³⁾
<i>Simulations for uncertainty analysis</i>		
Length of simulations (years)	20,000 ¹⁾	20,000 ²⁾
Calendar	Gregorian (365.2425 days per year with ordinary Gregorian leap day exceptions); simulations start in the year 2001 to avoid the major calendar correction in the year 1582	Gregorian (365.2425 days per year with ordinary Gregorian leap day exceptions); simulations start in the year 2001 to avoid the major calendar correction in the year 1582
Number of simulations	11 ¹⁾	24 ²⁾

Item	RG Rhine	RG Meuse
Block length in jack-knife procedure (years)	5 ¹⁾	3 ²⁾
# active years (original # years)	50 (55) ¹⁾	69 (72) ²⁾
Date of simulations	November 2012	May 2013
Names of NetCDF files (2000 years each)	Rhine_2012_v01.1_jackknife_20K_subseries01_part01.nc, ..., Rhine_2012_v01.1_jackknife_20K_subseries01_part10.nc to Rhine_2012_v01.1_jackknife_20K_subseries11_part01.nc, ..., Rhine_2012_v01.1_jackknife_20K_subseries11_part10.nc.	Meuse_2013_v01.1_mem4d_jackknife_20K_subseries01_part01.nc, ..., Meuse_2013_v01.1_mem4d_jackknife_20K_subseries01_part10.nc to Meuse_2013_v01.1_mem4d_jackknife_20K_subseries24_part01.nc, ..., Meuse_2013_v01.1_mem4d_jackknife_20K_subseries24_part10.nc
RG Program code	Fortran	Fortran
Random number generator	ran1 (Numerical Recipes)	ran1 (Numerical Recipes)
Seed random number generator	-21933 (default)	-21933 (default)
Relevant reports	KNMI Publication 186-I to 186-VII	KNMI Publication 196-I to 196-VI

¹⁾ For details see Schmeits, et al. (2014b), i.e. KNMI Publication 186-VII.

²⁾ For details see Schmeits, et al. (2014a), i.e. KNMI Publication 196-VI.

³⁾ For details see Buishand and Leander (2011), i.e. KNMI Publication 196-V.

5. How to update the RGs for the Rhine and Meuse basins with an extended base period

a. RG for the Rhine basin

For the WTI2017 version of the RG for the Rhine basin (i.e. the RG version of November 2012) the period of the historical data used for ‘driving’ the resampling procedure (i.e. data used in the feature vector) is exactly the same as the period of the historical data used for coupling with the hydrological model (i.e. 1951-2006). For future updates of the base period it is expected that this situation will not remain the same. The E-OBS data which is used for driving the resampling procedure is updated and extended every six months (and it is very likely that this situation will continue in the future) but it is uncertain (and probably unlikely) whether the HYRAS precipitation data (which is used for coupling with the hydrological model) will be extended and with what frequency. However, also without an update of the HYRAS data it is possible to update the RG for the Rhine basin. This can be achieved by extending the data used to drive the resampling procedure (i.e. E-OBS) and to add a second nearest-neighbour step to match the additional historical dates with historical dates of the data available for coupling with the hydrological model (i.e. HYRAS). This can (and should) be done in exactly the same way as done in the RG for the Meuse basin to account for the fact that the E-OBS data used for driving the resampling procedure will cover a longer period than the HYRAS data used for coupling with the hydrological model⁸. For this additional nearest-neighbour resampling step there is thus already (Fortran) program code available (see ‘Workflow for the RG for the Meuse basin’ in Appendix A: Workflow of the GRADE Rainfall Generators) which can easily be transferred to the RG code for the Rhine basin. For the Meuse basin the composition of the feature vector in this second nearest-neighbour resampling step differs somewhat from that in the primary nearest-neighbour resampling step. For details see Leander et al. (2005) page 1093 and Leander and Buishand (2004b) page 15.

b. RG for the Meuse basin

For the RG for the Meuse basin the situation is somewhat more complicated. For the WTI2017 version (i.e. the GRADE 2.0 version) of the RG for the Meuse basin (May 2013) the data used for driving the resampling procedure as well as the data used for coupling with the hydrological model were specifically collected and processed for GRADE. This in contrast to the E-OBS and HYRAS data used for the RG for the Rhine basin, which are ‘third party’ products. The basis for the historical data used for the RG for the Meuse basin are station data from France, Germany and Belgium. Besides these station data also basin-average precipitation data produced by RMIB are used. In 2011 the historical base period for the RG for the Meuse basin was extended with the years 1999-2008 (Buishand and Leander, 2011). For future updates of the historical base line data for the RG for the Meuse basin there are two options.

The first option is to repeat the update procedure of 2011. This new station data has to be bought again from essentially Météo France and RMIB⁹. The details of the data and the update procedure are described in Buishand and Leander (2011).

⁸ For the RG for the Meuse basin the (station) data used for driving the resampling procedure covers a longer period than the (sub-basin) data used for coupling with the hydrological model.

⁹ The Aachen (Germany) station data are publicly available from DWD.

Unfortunately, RMIB stopped producing the basin-average precipitation data for Belgium in 2007. For the French sub-basins the basin-average precipitation is calculated from the station precipitation using a standard interpolation procedure (i.e. Inverse Squared Distance interpolation), see Buishand and Leander (2011). This interpolation procedure could also be used to determine the basin-average precipitation for the Belgian sub-basins. But this would require daily precipitation data from many more Belgian precipitation stations than considered so far. Note that the retrieval of daily station data from Météo France and RMIB can be rather time consuming and, when many Belgian precipitation stations are needed also expensive. Ideally for WTI, agreements with Météo France and RMIB should be made for regular updates of these data.

Another difficulty can be that stations used for driving the simulations are closed or that inhomogeneities in their records cannot be easily adjusted. In that case it would be an option to select other driving stations. There are more precipitation stations that already start in 1946 or earlier (see Buishand and Leander (2011), page 15). It is recommended to update also the records of these stations¹⁰.

The second option would be to use the (updated) E-OBS data for driving the resampling procedure in the same way as currently already done for the RG for the Rhine basin, and to use the current 47/48-year basin-average precipitation and temperature data period (1961-2007/2008) for coupling with the hydrological model. This period could even be extended back to 1951, similar to the RG for the Rhine basin¹¹, since the RMIB data for the Belgian part are already available for the period 1951-1960. However the data for these 10 years for the French part have to be obtained from Météo France and to be interpolated to the French sub-basins as before. Any lack of overlap between the historical period of the 'driving' data and the historical period of the 'coupling' data can be dealt with by the second nearest neighbour step which is already in use for the RG for the Meuse basin. This would lead to a similar update structure/procedure as suggested for updating the base period for the RG for the Rhine basin. The main thing that has to be checked then is whether for the RG for the Meuse basin simulations driven with E-OBS data (interpolated to the 15 HBV-Meuse sub-basins) give similar results as the (present) simulations driven with station data. For the RG for the Rhine basin this turned out to be the case indeed. This may be less certain for the RG for the Meuse basin since the station density of E-OBS in the Meuse basin is rather poor. This may, however, also improve with future updates of E-OBS and therefore it is quite important to check whether 'driving' the RG for the Meuse basin with E-OBS data (with the latest available version of E-OBS, to be sure of the highest available station density) performs similarly as the version of the RG for the Rhine basin described in Schmeits et al. (2014b). This second option is probably more promising and efficient in terms of historical data retrieval and pre-processing of the data than the first one.

¹⁰ Regarding temperature two additional temperature stations (Langres and Reims) can be considered for which the data are already available for 1949 to 1998 (Leander and Buishand 2003).

¹¹ Note that 1951 is the year from which onwards the E-OBS data are available and for the RG for the Rhine basin also the start-year of the HYRAS precipitation data, i.e. the precipitation data which are actually coupled with the hydrological model. Using 1951 as the start-year for both the 'driving' data and the 'coupling' data gives currently the largest possible overlap between both types of precipitation data for the RG for the Rhine basin as well as for the RG for the Meuse basin.

6. Configuration of the RGs used for the uncertainty analyses

RG for the Rhine basin

Eleven jackknife series of 50 years were formed by leaving out subsequent non-overlapping 5-year blocks from the original series of 55 years (with the first block being 1952-56¹²). For each jackknife series a 20,000-year passive HYRAS simulation was conducted (the names of the NetCDF files of these simulations are given in Table 1).

RG for the Meuse basin

Twenty-four jackknife series of 69 years were formed by leaving out subsequent non-overlapping 3-year blocks from the original series of 72 years (with the first block being 1931-33¹³). For each jackknife series a 20,000-year simulation with a 4-day memory term was conducted similar to the 50,000-year reference simulation that includes all 72 years (the names of the NetCDF files of these jackknife simulations are given in Table 1). For the RG Meuse smaller blocks could be used in the jackknife method (3 years instead of 5 years; Schmeits et al, 2014a). This yields a more accurate estimate of the standard deviation of the estimated return level, since its variance decreases with decreasing block-size.

For all the programs and scripts described from step 2 onwards in Appendix A: Workflow of the GRADE Rainfall Generators, there is also a version to be used for the uncertainty analysis. These versions typically have 'unc' or 'jackknife' in their filename. For the jackknife simulations with the RGs for the Rhine and Meuse basins an adapted version of RESAMPLE.f is used. In these simulations the weights of the feature vector elements (see Table 1) are recalculated to account for the omitted historical data.

¹² More precisely 1 October 1951 – 30 September 1956. The start of a block was set at 1 October to avoid splitting the winter half-years.

¹³ More precisely, 1 October 1930 – 30 September 1933. Starting again at 1 October to avoid splitting the winter half-years.

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Appendix A

Workflow of the GRADE Rainfall Generators

This appendix describes in detail the workflow (the order in which all the necessary scripts and programs are run) for the RG for the Rhine basin (RG Rhine). The workflow for the RG for the Meuse basin (RG Meuse) is largely similar (the differences are described at the end of this appendix).

Workflow for RG Rhine

Unless stated otherwise the Fortran files (source code and executables) and shell scripts can be found (at KNMI) in:

`/usr/people/schmeits/GRADE/sources/`

- 1. Aggregate E-OBS daily precipitation/temperature or HYRAS daily precipitation data from their original grid to the 134 sub-basin values:** (resp. `thwt-EOBS` or `thwt-HYRAS`). This step is only needed when updates of either one of these datasets is available; E-OBS is updated 2 times per year, the update frequency of HYRAS unknown. This step contains a number of sub steps (E-OBS precipitation used as an example):

1a Run `thwt-EOBS`:

```
cat rhinebasins134.txt | ./thwt-EOBS -nc EOBS.nc -var rr
```

The file `rhinebasins134.txt` contains the contours of the 134 sub-basins and is needed as input for `thwt-EOBS` (or `thwt-HYRAS`).

1b Within IDL, run `convert_fortran_output`:

The program `convert_fortran_output` can be found in:
`/usr/people/schmeits/idl/IDL_Erwin/test_nnres*.pro`¹⁴
This program adds per sub-basin the historical date to the temperature/precipitation value (this is not done by `thwt-EOBS/thwt-HYRAS`).

```
IDL > convert_fortran_output,dataset,parameter
```

For example

```
IDL > convert_fortran_output,'e','rr'
```

in which `dataset = {'e' (for E-OBS), 'h' (for HYRAS)}` and
`parameter = {'rr', 'tg'}`.

1c Within IDL, run `change_filenames`:

The program `change_filenames` can be found in
`/usr/people/schmeits/idl/IDL_Erwin/calc_areal_prp_rhine.pro`

¹⁴ For this program it is relevant that the directory path used in the program corresponds with the actual directory structure. Possibly the path in the program should be updated. This should also be checked when this program is included in the (Deltares) SVN system for GRADE.

This program is needed since the numbering of the sub-basins (from ARCGIS) does not match with the HBV_Rhine numbering. The file `/usr/people/schmeits/GRADE/sources/arc.txt` contains the mapping of the ARCGIS- and HBV-numbering.
`IDL > change_filenames`

This last step (1c) was introduced after the difference in mapping was discovered (May 2012). Ideally steps 1b and 1c should be taken into account in the Fortran source code:

```
/usr/people/schmeits/GRADE/sources/thwt-EOBS.f and  
/usr/people/schmeits/GRADE/sources/thwt-HYRAS.f
```

2. Run the script `run_resample*.sh`:

The script `./run_resample*[_unc].sh` contains the core of the Weather Generator and does the actual resampling of the historical data prepared by the scripts/programs under step 1. The script runs successively a small number of programs which are summarized below.

Programs successively executed in the script:

- i. `fvectors(.f)`: calculates the Feature Vectors used in `resample`
- ii. `resample(.f)`: does the actual nearest-neighbour resampling
- iii. `backtran(.f)`: does the backtransformation of daily precipitation and temperature for all HBV sub-basins using standardized daily sub-basin data
- iv. `make_one_datafile(.f)`: calculates daily weighted areal averages of the whole river basin and adds all sub-basins to a single file.
- v. `ndaywi_leapyr_50000yr_nocumsum(.f90)` and `ndaysu_leapyr_50000yr_nocumsum(.f90)`: use the output file of iv to respectively calculate the sorted N -day winter- and summer maxima.

Note, running the programs in step 2 takes for a 50.000-year simulation for the Rhine about 12 hours on the systems used in 2013 (HP Z200; Intel Core i5 processor with a clock speed of 3.47GHz).

3. Within IDL, run `plot_gumbel_obs_sims`:

This (IDL) script `plot_gumbel_obs_sims` can be found in `/usr/people/schmeits/idl/IDL_Erwin/test_nnres*.pro`

This program uses the output of step 2.v and HYRAS and E-OBS data files and produces plots of the summer and winter half-year maxima of the 4-, 10- and 20-day precipitation sums.

```
IDL > plot_gumbel_obs_sims, ndays, season
```

For example

```
IDL > plot_gumbel_obs_sims, '10', 'winter'
```

in which `ndays = {'4', '10', '20'}` and `season = {'winter', 'summer'}`.

4. Run script `run_ncGRADE[_unc].sh`:

This (shell) script can be found in
`/usr/people/schmeits/GRADE/sources/netcdf-out/`

This script converts the ASCII files produced in step 2 to NetCDF files (files that contain both precipitation and temperature). In this step the Julian calendar, used in the resampling in step 2, is converted to the Gregorian calendar (which for each simulation starts in the year 2001 to avoid the big correction in the year 1582) because the Gregorian calendar is used by FEWS.

For several scripts there are different versions. The versions with extension ‘unc’ denote versions which are used in the uncertainty analysis (i.e. used for the set of jackknife simulations). No extension ‘unc’ means that the script is used for the reference simulation.

Workflow for RG Meuse

The workflow for RG Meuse is in many respects similar except that:

* The source directory (at KNMI) is:

`/usr/people/schmeits/GRADE/sources/meuse`

* There is no step 1 for the Meuse, since for the Meuse E-OBS is not yet used in the Feature Vector (FV) and no gridded data is available which can be used to construct the sub-basin average precipitation and temperature for the 15 HBV-Meuse sub-basins. The preprocessing of the Meuse data is described in detail in Leander and Buishand (2004b) and Buishand and Leander (2011).

* The script for step 2 is called `run_resample_test_maas*.sh`. In the backtransformation sub-program (step 2.iii) for RG Meuse an additional resampling step is applied to account for the time series of the sub-basin precipitation and temperature being shorter than the time series of station precipitation and temperature used in the FV. This is done by the script `backxfrrtg*.sc` (which in turn makes use of the program `backxform*.f`) rather than directly by the program `backtran(.f)` used for RG Rhine.

* The script to convert the ASCII files produced in step 2 to NetCDF files (step 4) is called `../netcdf-out/run_ncGRADE_Meuse[_unc].sh` and produces files that contain besides precipitation and temperature also potential evaporation. Before running `../netcdf-out/run_ncGRADE_Meuse[_unc].sh`, however, first the script `pet2_for_NG_Maas[_jackknife].sc` should be run. `pet2_for_NG_Maas[_jackknife].sc` calls the Fortran program `pet2_for_NG_Maas[_jackknife].f` and produces the ASCII files for potential evaporation using the ASCII files for temperature produced in step 2. Finally, `../netcdf-out/run_ncGRADE_Meuse[_unc].sh` also converts the old HBV-Meuse numbering that is used in the preprocessing of the Meuse data (to produce the sub-basin average precipitation and temperature data) to the new HBV-Meuse numbering used by FEWS.

Appendix B

Main Fortran sub-programs

- Program:** FVECTORS.F
- Purpose:** producing feature vectors spanning the required historical period
- Syntax:** FVECTORS *firstyr lastyr*
The arguments *firstyr* and *lastyr*, defining the historical interval for which the feature vectors are calculated, are compulsory.
- Input:** *firstyr* (format: YYYY)
lastyr (format: YYYY)
STDIN (list of filenames and weights)
Files containing historical rainfall and temperature data, as specified in STDIN (see 'Requires').
- Output:** STDOUT (*fvector-file*)
- Requires:** temperature and rainfall files for all stations or areas participating in the feature vectors, i.e. 'steering' the resampling.
Filenames are read from STDIN in the format:
filename_1 weight_1
filename_2 weight_2
.....
filename_N weight_N
Filenames whose extension begins with 't' (e.g. *filename.tm*) are treated as temperature. Filenames whose extension begins with 'r' (e.g. *filename.rr*) are treated as rainfall. The weights used in averaging over stations/areas need not be normalized (is taken care of in the program), and can thus have the value of e.g. the size of the area. If the weights are not explicitly specified, they are set to the default value of '1'.
- Provides:** ASCII file of feature vectors (STDOUT), one vector for each historical day in the period of interest in the format:
date average-rainfall average-temperature
rainfall-fraction
For each historical day the basin-average rainfall is obtained as the weighted average of the standardized daily rainfall amount over all historical rainfall sequences. Each rainfall sequence is standardized by dividing by the calendar-day mean-wet-day rainfall. Same for the average daily temperature of the temperature sequences, each of which is standardized by subtracting the calendar-day mean and then dividing by the calendar-day standard deviation. The rainfall fraction is the fraction of rainfall stations with rainfall of 0.3 mm or more. (Note: the fourth feature-vector element involved in RESAMPLE.F is used for the memory of the average rainfall and is calculated within RESAMPLE.F).
- Remarks:** FVECTORS also produces calendar-day shifts and scales for each historical record (.smr files for rainfall and .smt files for temperature). These files are required for standardizing historical and de-

standardizing resampled rainfall amounts and temperatures (program BACKTRAN.F).

Program: RESAMPLE.F
Purpose: Unconditional daily nearest-neighbour resampling in feature space, using a calendar day window of 121 or 61 days [today-60 days, today+60 days] or [today-30 days, today+30 days].
Syntax: RESAMPLE.F *simname* *fvector-file* *nyears* [*random-number-seed*]
The file *fvector-file* contains the feature-vector information produced by FVECTORS.F. The random number seed is optional and can be used to produce multiple independent sequences with the same settings.
Input: *fvector-file*
nyears (number of simulated years)
random-number-seed (integer; optional; default value = -21933)
Output: *simname.log* (resampled historical dates)
Requires: ASCII file containing feature vector data (currently 3D) for each historical day.
Provides: An index file *simname.log* with the historical dates for the *nyears* simulated years (*simname.log* is used by the program BACKTRAN.F)

Program: BACKTRAN.F
Purpose: generates the actual synthetic sequences from the index file produced by RESAMPLE.F.
Syntax: BACKTRAN *simname*
Input: *simname.log*
.smr and .smt files created by FVECTORS.F
STDIN (list of filenames, the same list that was used for FVECTORS.F can be used)
Output: For each filename in "list of filenames" a file is returned, with the same filename with the name of the simulation (*simname*) added. E.g. if "list of filenames" contains "Neckar.tm" and "Neckar.rr" and *simname* is "test0", the files "Neckar_test0.tm" and "Neckar_test0.rr" are created.
Requires:

- index file of simulation (*simname.log* produced by RESAMPLE.F)
- historical rainfall and temperature records for each variable to be simulated.
- smoothed scales and offsets for each calendar day (.smr and .smt files, provided by FVECTORS.F) for each variable.

Provides: generated sequences of each of the desired variables in the format: YYYYMMDD value
Remarks: The year YYYY runs from 1 up to the number of simulated years (*nyears*) and for each fourth year an additional day (leap day) is simulated. The scales and offsets are required to standardize the historical data and de-standardize resampled data.

General remarks

All used historical records should be in the format `YYYYMMDD value` and should be complete (no missing data allowed). Missing data can be found by looking for '-999.9' values in the `fvector-file`. In each year (including leap years) 365 historical days are used in the resampling procedure. In leap years the 31st of July is excluded and the 29th of February was kept in the simulation. The reason for this is that the winter half-year is considered the more important season.

The order in which to evoke the programs should be as follows:

```
FVECTORS firstyr lastyr <"file containing list of files (and weights) for  
rainfall and temperature" >fvector-file
```

```
RESAMPLE simname fvector-file nyears [rng_seed]
```

```
BACKTRAN simname <"file containing list of files for rainfall and temperature"
```

Note: '<' and '>' refer to redirection; '< file1' means: read from file1, rather than STDIN and '> file2' means: write to file2, rather than STDOUT. In the same way the file "file containing list of files for rainfall and temperature" can be created by:

```
ls *.r* *.t* > "file containing list of files for rainfall and temperature"
```

(UNIX/LINUX) or

```
dir *.r* *.t* /b > "file containing list of files for rainfall and temperature"
```

(DOS)

Appendix C

Metadata and structure NetCDF files

Meta data in NetCDF files RG Rhine

(> ncdump -h Rhine_2012_v01.1_reference_50K_part01.nc)

```
netcdf Rhine_2012_v01.1_reference_50K_part01 {
dimensions:
    time = UNLIMITED ; // (730485 currently)
    stations = 134 ;
    char_leng_id = 9 ;
    char_leng_name = 16 ;
variables:
    double time(time) ;
        time:standard_name = "time" ;
        time:long_name = "time" ;
        time:units = "days since 2001-01-01 00:00:00.0" ;
        time:calendar = "gregorian" ;
    double stations(stations) ;
    float latitude(stations) ;
        latitude:standard_name = "latitude" ;
        latitude:long_name = "Latitude values" ;
        latitude:units = "degrees_N" ;
    float longitude(stations) ;
        longitude:standard_name = "longitude" ;
        longitude:long_name = "Longitude values" ;
        longitude:units = "degrees_E" ;
    char station_id(stations, char_leng_id) ;
    char station_names(stations, char_leng_name) ;
    float rainfall_rate(time, stations) ;
        rainfall_rate:standard_name = "rainfall_rate" ;
        rainfall_rate:long_name = "rainfall amounts per day" ;
        rainfall_rate:units = "mm" ;
        rainfall_rate:FillValue = -9999.f ;
    float air_temperature(time, stations) ;
        air_temperature:standard_name = "air_temperature" ;
        air_temperature:long_name = "air temperature values" ;
        air_temperature:units = "degree_Celsius" ;
        air_temperature:FillValue = -9999.f ;

// global attributes:
    :title = "Daily precipitation and temperature time series from KNMI rainfall generator for Rhine basin
            (50K-year reference simulation Rhine 2012_v01.1)" ;
    :institution = "Royal Netherlands Meteorological Institute (KNMI)" ;
    :history = "created 01-11-2012; NetCDF-file created: 15-11-2013" ;
    :source = "Converted to NetCDF4, from output from KNMI rainfall generator" ;
    :version = "50K-year reference simulation Rhine 2012_v01.1" ;
    :features = "unconditional; weighted Euclidean; feature vector (P,T,F) weights: 2.33, 1.10, 6.38; memory: none; K: 10;
        moving window: 61; random number generator: ran1 (Numerical Recipes); random number seed: default (-21933)" ;
    :reference_data = "interpolated and aggregated observations (E-OBS/Hyras); E-OBS v7.0 1951-2006 (active, temp. and
        precip.); Hyras v2.0 1951-2006 (passive, precip. only); jackknife subseries: not applicable" ;
    :conventions = "CF-1.6" ;
    :comment = "This file has been generated using the NetCDF library in FORTRAN" ;
    :disclaimer = "Copyright Royal Netherlands Meteorological Insititute (KNMI)" ;
}
stations = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36,
37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54,
55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72,
73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90,
91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106,
107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120,
121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134 ;

latitude = , , , , , , , , , , , , , , , , , , , , , , , , , , , , , ,
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;

```


"Umos2 " ,
 "Umos3 " ,
 "Umos4 " ,
 "Obsi " ,
 "Misi " ,
 "Agger " ,
 "Unsi " ,
 "Erft1 " ,
 "Erft2 " ,
 "Erft3 " ,
 "Ruhr1 " ,
 "Ruhr2 " ,
 "Ruhr3 " ,
 "Ruhr4 " ,
 "Lippe1 " ,
 "Lippe2 " ,
 "Lippe3 " ,
 "AlbPfinz " ,
 "QueichSpeyerbach" ,
 "UpRhine1 " ,
 "UpRhine2 " ,
 "UpRhine3 " ,
 "WeschnitzModau " ,
 "UpRhine4 " ,
 "Selz " ,
 "Wisper " ,
 "MidRhine1 " ,
 "MidRhine2 " ,
 "Saynbach " ,
 "Nette " ,
 "Wied " ,
 "Ahr " ,
 "MidRhine3 " ,
 "MidRhine4 " ,
 "Wupper1 " ,
 "LowRhine1 " ,
 "LowRhine2 " ,
 "Emscher " ,
 "LowRhine3 " ,
 "LowRhine4 " ,
 "Wupper2_out " ,
 "UpRh2_1 " ,
 "ElzDreis1 " ,
 "ElzDreis2 " ,
 "Kinzigup " ,
 "UpRh2_2 " ,
 "Ill1 " ,
 "Ill2 " ,
 "Fecht " ,
 "Bruche " ,
 "Ill3 " ,
 "Kanal " ,
 "Moder " ,
 "Zorn " ,
 "SauerWieslauter " ,
 "MurgRench " ,
 "UpRh2_3 " ,
 "Rhein1 " ,
 "Rhein2 " ,
 "Bodensee " ,
 "Thur " ,
 "Rhein_3 " ,
 "Thuner_s " ,
 "Aare1 " ,
 "Bieler_s " ,
 "Emme " ,
 "Vierwa_s " ,
 "K1_Emme " ,
 "Zurich_s " ,
 "Lim_reus " ,
 "Aare2 " ,
 "Schwarzw " ,
 "Birs " ,
 "Rhein4 " ;

Meta data in NetCDF files RG Meuse

(> ncdump -h Meuse_2013_v01.1_mem4d_reference_50K_part01.nc)

```
netcdf Meuse_2013_v01.1_mem4d_reference_50K_part01 {
dimensions:
    time = UNLIMITED ; // (730485 currently)
    stations = 15 ;
    char Leng_id = 9 ;
    char Leng_name = 16 ;
variables:
    double time(time) ;
        time:standard_name = "time" ;
        time:long_name = "time" ;
        time:units = "days since 2001-01-01 00:00:00.0" ;
        time:calendar = "gregorian" ;
    double stations(stations) ;
    float latitude(stations) ;
        latitude:standard_name = "latitude" ;
        latitude:long_name = "Latitude values" ;
        latitude:units = "degrees_N" ;
    float longitude(stations) ;
        longitude:standard_name = "longitude" ;
        longitude:long_name = "Longitude values" ;
        longitude:units = "degrees_E" ;
    char station_id(stations, char Leng_id) ;
    char station_names(stations, char Leng_name) ;
    float rainfall_rate(time, stations) ;
        rainfall_rate:standard_name = "rainfall_rate" ;
        rainfall_rate:long_name = "rainfall amounts per day" ;
        rainfall_rate:units = "mm" ;
        rainfall_rate:FillValue = -9999.f ;
    float air_temperature(time, stations) ;
        air_temperature:standard_name = "air_temperature" ;
        air_temperature:long_name = "air temperature values" ;
        air_temperature:units = "degree_Celsius" ;
        air_temperature:FillValue = -9999.f ;
    float reference_evaporation(time, stations) ;
        reference_evaporation:standard_name = "reference_evaporation" ;
        reference_evaporation:long_name = "potential evapotranspiration amount per day" ;
        reference_evaporation:units = "mm" ;
        reference_evaporation:FillValue = -9999.f ;

// global attributes:
    :title = "Daily precipitation, temperature and evaporation time series from KNMI rainfall generator for Meuse basin
(50K-year simulation Meuse 2013_v01.1_mem4d)" ;
    :institution = "Royal Netherlands Meteorological Institute (KNMI)" ;
    :history = "created 03-05-2013; NetCDF-file created: 13-12-2013" ;
    :source = "Converted to NetCDF4, from output from KNMI rainfall generator (P and T) and from pet2.f (PET)" ;
    :version = "50K-year simulation Meuse 2013_v01.1_mem4d" ;
    :features = "unconditional; weighted Euclidean; feature vector (P,T,F,M) weights: 2.19, 1.05, 0, 0.30; memory: 4;
K: 10; moving window: 121; random number generator: ran1 (Numerical Recipes); random number seed:
default (-21933)" ;
    :reference_data = "station series for active simulation (temperature and precipitation: 1930-1939 & 1945-2008); series
for simulation of HBV subbasins (temperature: 1967-2008; precipitation: 1961-2007) [See KNMI-publication
196-V (2011)]; PET simulated using simulated T and Eq. 5 in Leander and Buishand (2007) [Journal of Hydrology,
332, 487-496]; jackknife subseries: not applicable" ;
    :conventions = "CF-1.6" ;
    :comment = "This file has been generated using the NetCDF library in FORTRAN" ;
    :disclaimer = "Copyright Royal Netherlands Meteorological Institute (KNMI)" ;
}

stations = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 ;

latitude = _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ ;

longitude = _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ ;

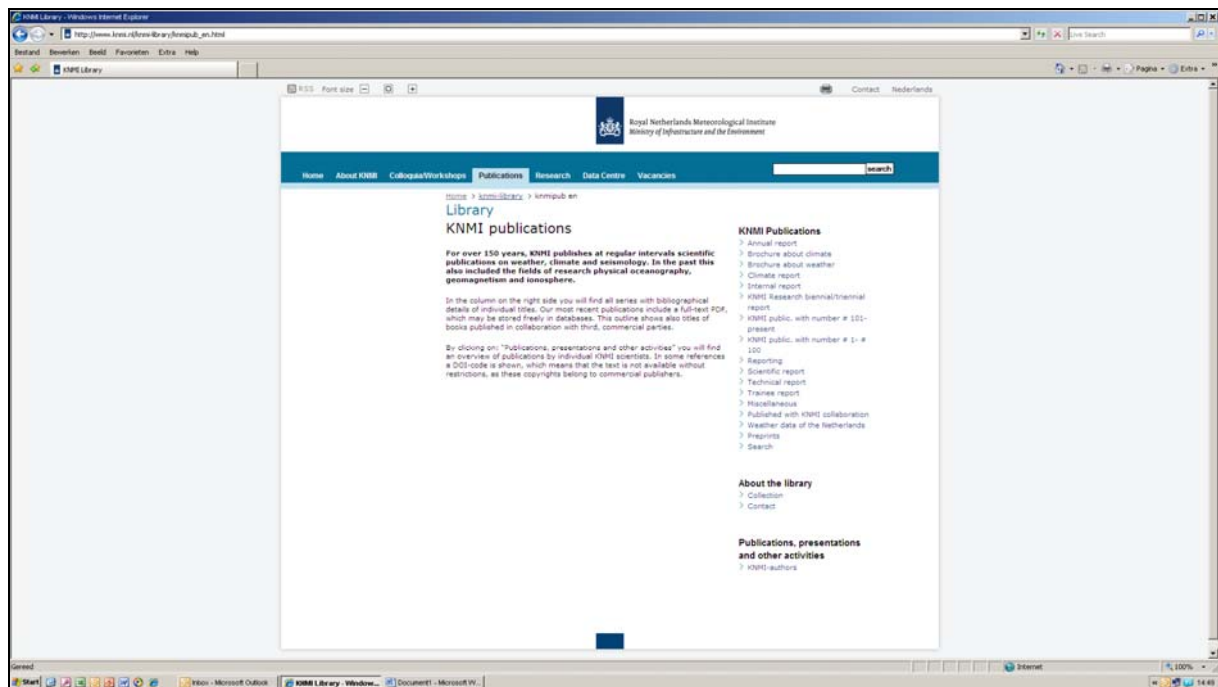
station_id =
    "I-MS-0001",
    "I-MS-0002",
    "I-MS-0003",
    "I-MS-0004",
    "I-MS-0005",
    "I-MS-0006",
```

```
"I-MS-0007",  
"I-MS-0008",  
"I-MS-0009",  
"I-MS-0010",  
"I-MS-0011",  
"I-MS-0012",  
"I-MS-0013",  
"I-MS-0014",  
"I-MS-0015";
```

```
station_names =  
"Lorraine Sud ",  
"Chiers ",  
"Lorraine Nord ",  
"Bar etc ",  
"Semois ",  
"Viroin ",  
"Maas Chooz-Namur",  
"Lesse ",  
"Sambre ",  
"Ourthe ",  
"Ambleve ",  
"Vesdre ",  
"Mehaigne ",  
"Maas Namur-Monsi"(n),  
"Jeker ";
```


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