How to obtain probabilistic discharge scenarios for the Meuse and the Rhine rivers?

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Introduction

In addition to probabilistic sea level rise (SLR) scenarios along the Dutch coast, RWS expressed the need for probabilistic scenarios of extreme river discharge of the Meuse and Rhine rivers where these enter the Netherlands. KNMI released, respectively in 2006 and 2014, the KNMI'06 and KNMI'14 climate scenarios, but these scenarios are by definition not probabilistic in nature. Le Bars et al. (2016) made for RWS a first assessment of such probabilistic scenarios/projections of sea level rise along the Dutch coast. These probabilistic projections are conditional on so-called IPCC RCPs (Representative Concentration Pathways). Two of these RCPs (i.e. RCP 4.5 and RCP 8.5) are considered in more detail by Le Bars *et al*. (2016).

RWS/Deltares/KNMI methodology for construction river discharge scenarios

RWS, Deltares and KNMI work together for several years in the field of constructing future river discharge scenarios. So far the basis for these discharge scenarios were the "KNMI climate scenarios"; i.e. the KNMI'06 scenarios in 2006 (also used in the Deltascenario's developed in 2011) and the KNMI'14 scenario's in 2014 (of which the accompanying KNMI'14 scenarios for the Rhine and Meuse were finished in 2015). The methodology consists of a number of steps/models. Meteorological time series serve as input to hydrological and hydraulic models that convert the precipitation in the river basin into river discharge at various locations along the river (with Lobith (Rhine) and Borgharen (Meuse)of main interest to RWS). From the resulting discharge time series the relevant discharge statistics are derived, such as annual/seasonal/means and the return levels for the return periods of interest. This is done with meteorological time series which are representative for the current (unperturbed) climate (e.g. observed historical time series) as well as for meteorological time series which are representative for the future (perturbed) climate. These 'future meteorological time series' are constructed by perturbing/transforming the 'current meteorological time series'. The method therefore also contains elements of so-called Delta(-change) methods. The transformation can be based on the changes (deltas) provided by a climate change scenario (such as e.g. given by the KNMI'14 climate scenarios or on the changes (deltas) as derived from a particular climate model simulation (which can actually also be regarded as a climate scenario but which is typically denoted as a climate projection). The simulations with the hydrological model using the 'future meteorological time series' as input, result in discharge time series representative of the future climate. From these 'future discharge time series' again the relevant discharge statistics are derived, but now for the future climate and the difference between the discharge statistics of the future – and current climate essentially is the future discharge scenario.

A limitation of this method is that historical meteorological time series covering the whole river basin (with a required temporal (i.e. daily) and spatial (i.e. hydrological sub-basins) resolution) typically are not longer than about 50 years. For the Rhine we have 56-year (1951-2006) daily precipitation and temperature time series for 134 HBV-Rhine sub basins and for the Meuse 41-year (1967-2007) series for 15 HBV-Meuse sub basins. From such 'short' series it is possible to derive (the changes in) the annual/seasonal/monthly mean discharges, and discharge return levels up to return periods of about 10 years (Q_{10}), but definitely not the discharge return levels of return periods of 1250 years (Q_{1250}) and up to 30.000 years ($Q_{30,000}$) that are required by RWS for the new probabilistic framework (at least not without fitting a probability distribution and extrapolation to almost 3 orders of magnitude!).

…This is exactly the reason why the GRADE instrument/methodology was developed (GRADE = Generator of Rainfall And Discharge Extremes). GRADE consists of a stochastic rainfall/weather generator (RG) with which synthetic 50.000 (50K) year meteorological time series with a daily resolution are simulated. For brevity, and since it is not relevant for the message here, we don't go into de details of the RG. In GRADE the RG provides the meteorological input to the same hydrological and hydraulic models for the Rhine and the Meuse as mentioned above. The methodology is further exactly the same, the only difference is that with GRADE 50K-year discharge time series are produced in contrast to those based on the historically observed ~50-year meteorological time series. An increase of a factor 1000 thus, which also makes it possible to derive/estimate Q_{1250}, $Q_{10.000}$ and even $Q_{30.000}$.In the same way as for the historically observed ~50-year meteorological time series the synthetic 50K-year meteorological time series in GRADE (generated with the RG) can be 'transformed' to represent future climate conditions, and GRADE can thus be used to construct/derive future scenarios of extreme discharges such as Q_{1250} and $Q_{10.000}$. GRADE for the current climate is actually used for WBI (previously WTI) and GRADE combined with the KNMI climate scenarios is used for OI. Further details of GRADE and the use of GRADE in combination with the KNMI'14 climate scenarios are presented in Sperna Weiland *et al.* (2015).

What is needed to construct probabilistic discharge scenarios?

There are thus already discharge scenarios for the Rhine and the Meuse based on the KNMI'14 scenarios (and previously such scenarios were derived for KNMI'06). In this section it is described how probabilistic discharge scenarios, i.e. probabilistic scenarios conditional on RCPs as for SLR described in Le Bars *et al*. (2016), can be constructed given the methodology that is currently used to derive the discharge scenarios based on the KNMI climate scenarios.

From the above it is clear that KNMI'14 discharge scenarios based on both the ~50-year observed historical series and the 50K-year synthetic GRADE series have already been produced (Sperna Weiland *et al.,* 2015). In addition, in Sperna Weiland *et al.* (2015), discharge projections have been produced based on 183 CMIP5 climate model runs for which (daily) changes in precipitation and temperature were available. For each of these 183 members the ~50-year historical meteorological series were transformed in such a way that the climate of the transformed series represents the climate of each member (in the same way as for each of the four (five) KNMI'14 climate scenarios). These 183 runs include all four RCPs (54 runs represent RCP 4.5 and 55 represent RCP 8.5). In Sperna Weiland *et al.* (2015) all 183 runs were combined into a single group and from these 183 runs, 2.5 to 97.5% confidence intervals were derived for the relevant discharge statistics and these confidence intervals were compared with the results/changes derived from the KNMI'14 scenarios.

To produce probabilistic scenarios conditional on the RCPs these 183 CMIP5 runs would be grouped per RCP and from the ~50 members per RCP a mean and a standard deviation for the change in de discharge statistic of interest is calculated. Assuming a Normal distribution, from this mean and standard deviation easily a pdf can be derived. Note that the basic information of such an exercise based on the CMIP5 runs is already available, or could be produced "relatively easy" (with the help of Deltares) based on future CMIP6 climate model simulations. But since in this 'exercise' only the ~50-year (historical) series are used, the discharge statistics for which pdfs can be produced in this way is limited to the changes in annual/seasonal/monthly means, low discharges such as the mean annual lowest 7-day Q (denoted as NM7Q), the mean annual max. Q (denoted as MHQ and having the order of magnitude of Q_2) and the once in 10-year discharge (Q_{10}). But definitely not Q_{1250} or $Q_{10.000}$.

But we have GRADE!? Yes we have GRADE, and in theory we could use GRADE in exactly the same way as the ~50-year series are used. But GRADE is computationally expensive, in fact it is computationally too expensive to apply to all ~200 CMIPs runs. For comparison, for KNMI'14 we applied it only to the 4 KNMI'14 scenarios and this was already a big effort, an about 50 times larger effort seems not realistic (transforming the 50K-year meteorological series to each of the 4 KNMI'14 climate scenario's was already a big effort (by KNMI) and running the hydrological and hydraulic models on 4 50K-year series (by Deltares) was also a big effort). Wat can we do then? Isn't it possible to use GRADE at all for the purpose of deriving probabilistic scenarios for the changes in Q_{1250} and $Q_{10.000}$? Yes, it is. As an alternative to using GRADE with all ~200 CMIP5 runs, GRADE can be used with, per RCP, only a selected small number of CMIP5 runs (with a minimum of 2 runs per RCP). But for this we have to make an assumption. The assumption is that the results, obtained with GRADE, e.g., the Q_{1000}'s, for these selected CMIP5 runs, are lying in the same position of the 'GRADE results pdf' as e.g. the Q_{10}'s (of these same CMIP5 runs) ly in the '50-year results pdf'. In other words and illustrated with an example based on the use of (the minimum of) 2 CMIP5 runs. These 2 members are denoted as member *a* and member *b*. The assumption means that:

$Pr[dQ_{1000} \leq dQ_{1000}(a)] = Pr[dQ_{10} \leq dQ_{10}(a)] = x$ (e.g. 0.1 or 10%) and

$Pr[dQ_{1000} \leq dQ_{1000}(b)] = Pr[dQ_{10} \leq dQ_{10}(b)] = y$ (e.g. 0.9 or 90%),

With Pr denoting the (cumulative) probability. From these two probabilities and $dQ_{1000}(a)$ and $dQ_{1000}(b)$, and again assuming a Normal distribution a mean and standard deviation can be calculated[1] for dQ_{1000} which determine the full pdf for dQ_{1000}. And similar for all other quantiles/return discharges required, in a formula:

$Pr[dQ_T \leq dQ_T(a)] = x$ and

$Pr[dQ_T \leq dQ_T(b)] = y,$

for all dQ_T with T > 10 years obtained using GRADE.

Thus, with this assumption, 'full GRADE simulations' for two selected CMIP5 runs (per RCP, and time horizon) are sufficient to estimate/derive a pdf for dQ_T with T > 10 years. This is thus a gain of almost a factor 100 in the number of expensive GRADE simulations. Per time horizon and all four RCPs this is (only) twice the amount of full GRADE simulations as were performed for KNMI'14 (Sperna Weiland *et al*. 2015). However, by using full GRADE simulations for only two selected CMIP5 runs could make the final pdf for dQ_T with T > 10 years relatively sensitive to the individual change characteristics in these two CMIP5 runs. Instead of the minimum of two CMIP5 runs, also a small number of runs could be selected, and the mean and standard deviation of dQ_T could be fitted (linearly) to the individual dQ_T's. For example, with 5 CMIP5 runs these runs could be chosen in such a way that $Pr[dQ_{10} \leq dQ_{10}(i)]$ is e.g. 0.10, 0.25, 0.50, 0.75 and 0.90.

About the validity of this assumption. This is difficult to check. An indication could be obtained by checking whether the exceedance probabilities of e.g. $dQ_2(I)$ and $dQ_{10}(i)$ are the same in the two selected runs. If this is the case it might be an indication than this is also true for $dQ_{10}(I)$ and $dQ_{1000}(i)$ (but definitely no proof), if not, it is likely not to be true for $dQ_{10}(I)$ and $dQ_{1000}(i)$ either.

[1] Using Px(μ,σ) = μ + σ Px(0,1), with Px the x-th percentile (quantile) of the Normal distribution.

Points of attention

* Mainly for the Rhine, for very large discharges, there is, as a result of upstream flooding in parts in Germany, an effective reduction of peak discharges at Lobith. This phenomenon gets serious attention at the moment but it is still not possible to quantify how large this effect exactly is under different conditions (due to a lack of a suitable hydraulic model). But from this it is already clear that for very large discharges a Normal pdf (for the change in large Q_T's) becomes very doubtful. If we want to model this effect properly in the ultimate pdf for very large discharges, i.e, for dQ_T with T > 1000 years, considerably more than 2 CMIP5 model runs using GRADE will be needed to produce an non-Normal pdf. The assumption $\Pr[dQ_T \leq dQ_T(i)] = \Pr[dQ_{10} \leq dQ_{10}(i)]$ for T > 1000 may under those conditions also become more problematic.

* The above framework asks for a continued close collaboration between KNMI and Deltares. KNMI can produce the transformed synthetic meteorological series based on selected CMIP5 runs (which are part/the start of GRADE) but Deltares should be involved to perform the subsequent hydrological and hydraulic calculations/simulations. Together Deltares and KNMI can select the (small number) of relevant CMIP5 runs. Which are the most suitable selection criteria is something to think about. Both the transformation and the hydrological/hydraulic simulation of the 50K-year GRADE series are computationally intensive. The amount of work this involves should not be underestimated.

* The amount of time, at least the computation time, increases linearly with the number of time horizons (and the number of RCPs). In Le Bars *et al*. (2016) pdfs for four time horizons are produced 2030, 2050, 2070 and 2090 (based on the 20-year periods around these time horizons. For KNMI'14 (for the Rhine and the Meuse basins) we distinguish two time horizons 2050 and 2085 (based on 30-year periods around these horizons) while for the 183 CMIP5 climate model runs, that have already been processed, and that are therefore directly available, the time horizons effectively are 2035 and 2085. An additional effort would be needed to adapt the ADC-transformation tool[2] for the CMIP5 climate models to different time horizons than the latter two.

[2] Adaptation actually means here calculate and include the ADC-transformation coefficients for different time horizons than those currently available. For details about the ADC-transformation method see: van Pelt *et al*. (2012).

Meteorological reference time series (current climate)	Historical meteo series (daily P and T) Rhine: 1951-2006 (134 HBV-Rhine sub basins) Meuse: 1967-2007 (15 HBV-Meuse sub basins)	GRADE Synthetic meteo series (daily P and T) Both Rhine and Meuse: 50,000 years (134 HBV-Rhine and 15 HBV-Meuse sub basins)
KNMI'14	Reference historical series transformed to each of the 4* KNMI'14 climate scenarios both for 2050 and 2085 *: For Rhine and Meuse actually 5 scenario's since W_H split into W_H and $W_{H, dry}$	Reference synthetic series transformed to each of the 4 KNMI'14 climate scenarios both for 2050 and 2085 Note: no $W_{H, dry}$ since not relevant for extreme discharges (which are winter phenomena)
Probabilistic scenarios per RCP	Reference historical series transformed to each of the 183 CMIP5 runs: RCP 2.6: 45 RCP 4.5: 54 RCP 6.0: 29 RCP 8.5: 55 for both 2035 and 2085. Used to construct 2.5 to 97.5% confidence intervals of dQ(HBV) from all 183 runs together.	Nothing has been done here yet. This is computationally very expensive, and definitely TOO expensive to do for all ~200 CMIP5 runs
	Used for Changes in/scenarios for mean and low discharges: * dMQ (mean annual/seasonal/monthly Q) * dMHQ (mean annual max Q; ~ Q_2) *dNM7Q (mean annual lowest 7 day Q)	**Used for** Changes in/scenarios for extremely high discharges (discharge return levels): * dQ_T with T >> 10 years (up to T = 30,000 years)

References

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