Estimating the combined effect of flood mitigation measures

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ABSTRACT: When trying to identify combinations of flood mitigation measures that meet a particular target for flood level lowering, a simple and commonly applied method is to estimate the combined effect by superimposing simulated flood-level-lowering effects of the individual measures. This approach has been used in early stages of the Room for the River program in the Netherlands to limit the range of potential solutions for improved flood safety along the Dutch rivers. While this method allows quick evaluations and is also easily implemented, it may yield significant errors in the estimated overall flood-lowering effect due to neglect of interference between measures. Consequently, expected effects of "suitable" combinations of measures may be overoptimistic, while other more effective combinations may not receive the consideration that they deserve. To obtain more reliable estimates of the combined flood-level lowering effect we propose a new method that takes into account the interference between separate measures. We applied this proposed corrected-discharge method (CDM) to a case, in which maximum errors in estimated water levels of the River Meuse were reduced by 81% as compared to the outcomes from the original method that uses straightforward addition of effects. The new method still allows quick evaluation of combinations of measures and can therefore be used in the planning and early design phases of complex flood mitigation programs. The CDM also has potential for real-time application during a flood threat when the question arises of how to optimally deploy retention areas.

1 INTRODUCTION

In recent years, river management strategies worldwide have increasingly acknowledged the importance of a basin-wide approach. For example, in the Dutch 'Room for the River' program a shift was made in national river management strategy from dike strengthening to mitigate local flood threat towards regional discharge accommodation (RWS, 2006). As part of this strategy a spatially-variable hydraulic objective, or *flood level lowering target*, was defined to quantify the minimum reduction in water level to meet required flood protection levels along the Dutch rivers. To fulfill this target, numerous measures were taken into consideration, including retention areas, lowering of flood plains, dredging, removing of hydraulic obstacles and dike relocation (Silva et al. 2001). This large number of potential measures yields an even larger number of possible combinations of measures. To aid the selection of suitable combinations, the decision support tool *Planning Kit PKB* was developed (Deltares 2006; see Figure 1). Here, we show the usefulness of this Planning Kit, and propose a new procedure to improve the accuracy of estimated flood level impacts for combinations of measures.

The Planning Kit PKB is based on pre-compiled data of individual flood mitigation measures. This database holds effects and characteristics of individual measures from various different sources, such as flood level impacts that have been calculated using 1D and 2D hydrodynamic models, but also holds other relevant metrics such as ecological value and cost efficiency. By selecting several measures, the Planning Kit uses simple superposition of metrics (flood impacts, costs) to give an overall view of the situation when measures are combined. The advantage of this approach is that it allows rapid evaluation of combinations of measures, which is helpful in early planning stages if many combinations of measures are possible (e.g. Van der Klis and de Bruijn, 2007). However, it is also widely recognized that superimposing these metrics, in particular superimposing water level effects, may lead to large errors. For example, Miguez et al. (2009) found that flow patterns and wave propagation can be influenced by flood mitigation measures in such a way that measures located up- or downstream can have a different effect on the water levels than where they were designed for. Also, research along the Cornia and Arno rivers (Italy) shows that upstream detention basins cause bigger flood peaks downstream (Pagliara 2006).

For the Dutch part of the Rhine River, which has little water storage areas in the basin, it is found that the simple superposition approach gives errors in estimated combined flood impacts up to ~5 cm, which is only a small fraction of the total flood level lowering effect of the measures (Van Schijndel, 2005). However, along the Meuse River, errors may be as large as several decimeters as a result of the non-linear interaction between lowering of the floodplains and deployment of retention areas (Reuber et al. 2006). In general, it appears that estimates based on superposition of individual flood level impacts are acceptably accurate if measures mostly affect the discharge carrying-capacity of the river. However, these estimates become less accurate whenever retention effects play an important role. Therefore, if retention measures are prominent in a river basin, applying a simple superposition of flood level impacts of measures may give a misleading view of their overall performance. This could lead to non-optimal combinations of measures, which may not fulfill the flood level target, or lead to over-designed measures that request unnecessary high investments. Conversely, other combinations of measures may not receive serious consideration, while their combined functioning may actually be more effective.

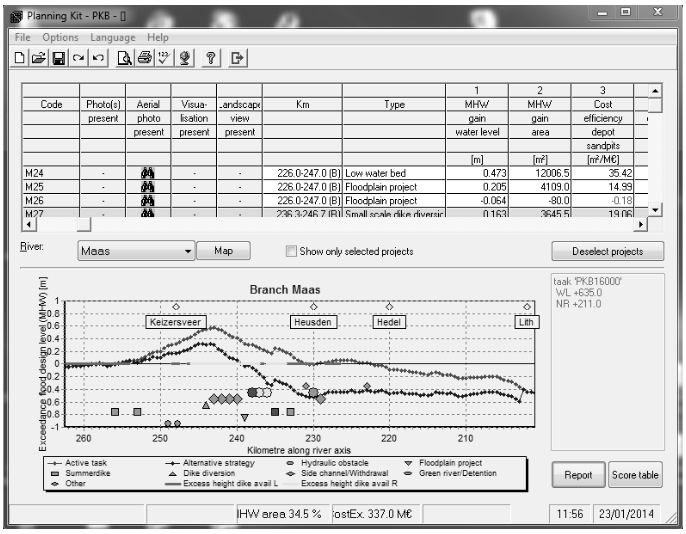
In the current work, we propose to expand on the capabilities of a decision support tool as the Planning Kit PKB, by maintaining its ability to quickly combine flood mitigation measures and estimate their combined effect, while improving its capability of estimating the combined effect of measures when the interaction between measures plays an important role. For this purpose, we propose a new algorithm for combining flood effects of separate flood mitigation measures and compare its performance to the traditional approach of combining flood effects.

2 METHODOLOGY

2.1 *Traditional approach: simple superposition (SS)*

As mentioned earlier, in the Planning Kit PKB (Figure 1) flood level impacts of individual measures are added together to get an estimate of the combined effect of the measures. The individual effects per measure are available from previously performed 1D or 2D hydrodynamic simulations, where the flood level lowering effect per measure was calculated under passing of a flood wave (i.e. a design discharge event Q_{Ref}). Figure 1 shows how selection of two measures in the Planning Kit PKB gives the estimated combined flood level lowering effect by simply superimposing their individual effects over the defined flood level lowering target. In the remainder of this work we will refer to this method as the *simple superposition* (SS) method.

It is important to note that in the Planning Kit PKB a simplified correction factor is incorporated to account for the lower effectivity of retention measures if interaction with surrounding measures is taking place. For this purpose a constant reduction factor of 0.5 is applied to the flood level effect of retention measures (Van Schijndel 2005).



Code	Photo(s) present	Aerial photo present	Visua-lisation present	andscape view present	Km	Type	1 MHW gain water level [m]	2 MHW gain area [m^2]	3 Cost efficiency depot sandpits [m^2/M€]
M24	-	🔭	-	-	226.0-247.0 (B)	Low water bed	0.473	12006.5	35.42
M25	-	🔭	-	-	226.0-247.0 (B)	Floodplain project	0.205	4109.0	14.99
M26	-	🔭	-	-	226.0-247.0 (B)	Floodplain project	-0.064	-80.0	-0.18
M27	-	🔭	-	-	236.3-246.7 (B)	Small scale dike diversic	0.163	3645.5	19.06

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Figure 1. The Room for the River *Planning Kit PKB* (Deltares, 2006): a decision support tool that estimates effects of combined river engineering measures in terms of flood level impacts, costs, spatial impact and various other metrics. The dark symbols in the inset graph mark the selected measures. The lower line in the inset graph show the remaining flood level target after accounting for the effect of the selected measures.

2.2 *New approach: corrected-discharge method (CDM)*

To account for interaction between individual measures in a support tool as the Planning Kit PKB, we propose an alternative method to estimate the overall combined flood level impact of the measures. In the proposed corrected-discharge method (CDM), again, an estimate of the overall impact on flood levels is made by superimposing impacts of individual measures at a particular discharge event Q_{Ref}. However, this time, the individual flood level impacts per measure are based on a measure-specific calculated ‘effective discharge’ Q_{Eff}, which takes into account the influence of surrounding measures on the effectivity of the measure under consideration. For example, if at a particular measure-location the surrounding measures cause flood levels to drop, say, 50 cm, then the individual flood-level-lowering impact at this location should not be evaluated at Q_{Ref} but at Q_{Eff}, which corresponds to the 50 cm lowered stage. Such a corrected Q_{Eff} will be calculated for each individual measure (M_i), denoted by $Q_{Eff,i}$. For this procedure to work it is required that for each measure a specific point-location X_i is defined where the influence of external measures is evaluated. Next, for each individual measure, the water level effect

dH_i is calculated at discharge $Q_{Eff,i}$ and the combined water level dH_{Tot} is calculated by adding all dH_i together (just as in the standard procedure from Section 2.1). This procedure will be repeated until the updated values for dH_i, $Q_{Eff,i}$ and the combined flood level effect dH_{Tot} no longer change. The algorithm for this iterative procedure is given below.

1. Calculate the combined flood level effect dH_{Tot} by adding together all water level effects of the selected measures: $dH_{Tot} = \Sigma\, dH_i$.
2. Next, for each measure M_i:
   a. calculate the "external water level effect" $dH_{ext,i}$, which is the combined effect due to all measures *excluding* measure M_i: $dH_{ext,i} = dH_{Tot} - dH_i$.
   b. evaluate the external water level effect $dH_{ext,i}$ at location X_i, i.e. $dH_{ext,i}(X_i)$.
   c. calculate the change in discharge dQ_i that corresponds with $dH_{ext,i}(X_i)$, using the rating curve at location X_i,
   d. calculate the effective discharge at location X_i as $Q_{Eff,i} = Q_{Ref} + dQ_i$.
   e. evaluate the water level effect of measure M_i at discharge $Q_{Eff,i}$. This gives the new corrected dH_i.
3. Repeat steps 1 and 2 until $Q_{Eff,i}$ and dH_{Tot} no longer change.

The proposed algorithm requires that for the reference situation (no measures) the water levels are available for a range of discharge values that is wide enough to cover stage-changes by amount dH_{Tot}. These data allow us to define rating curves at each measure location, needed to calculate dQ_i (step 2c). Next, in order to evaluate the corrected dH_i in step 2e, the water level effects per individual measure should be available for this same range of discharge values. The following section will demonstrate the proposed method as applied to a case using flood effects of retention measures along the river Meuse.

3 CASE: MEUSE RIVER

In this study we selected the Meuse River in the Netherlands as our example case because this river holds several retention areas that may become active under flood conditions. Therefore, this river seems suitable for investigating the appropriateness of superpositioning flood impacts of individual retention measures, which, in reality, are known to influence each other's functioning.

The Meuse River originates in France and runs through Belgium and the Netherlands before draining in the North Sea (Figure 2). The total length of the river is about 950 km, of which roughly 250 km are in the Netherlands. The location markers in this study refer to the Dutch part of the river Meuse (measured along river axis, see Figure 3). The average discharge in the Dutch part of the Meuse is approximately 270 m^3/s (Ashagrie et al., 2006) and a design peak discharge of 3800 m^3/s, corresponding to a 250yr return period (a "250yr flood"), is used as flood protection standard (Barneveld et al. 2003).

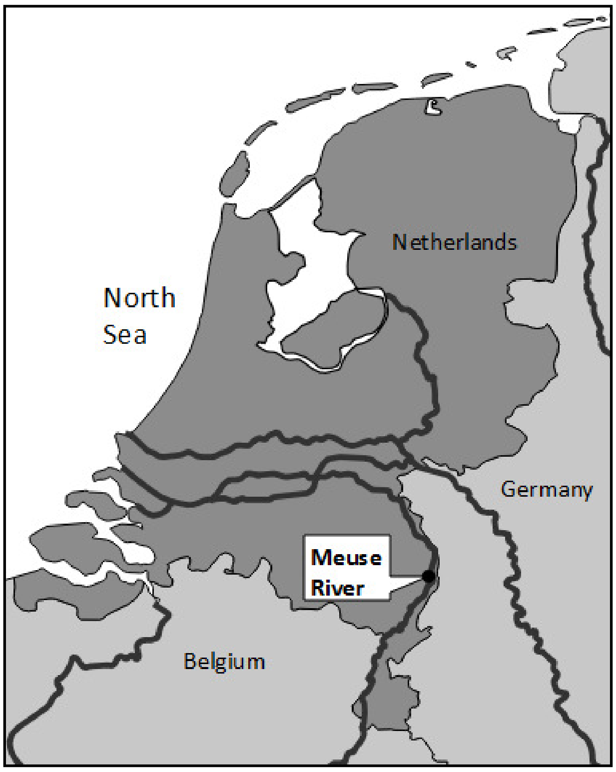

Figure 2. The River Meuse in the Netherlands.

A 1-dimensional hydrodynamic river model is available for the Meuse that has been used in the Netherlands for a variety of river management purposes (Barneveld et al., 2003). The model covers the entire 250km of the Dutch part of the Meuse, along which 38 retention measures are present. Figure 3 shows the model results (maximum water levels) along a subsection of Meuse when using the adapted 250yr design flood wave as inflow boundary, corresponding to a future climate scenario with a 20% increase in peak discharge (the shape of the used flood wave is shown in Figure 4, thick line). The locations and inflow-heights of retention measures along this river section are also shown (the river section in Figure 3 contains only 27 of the 38 measures). Figure 3 shows the results from two model runs: one with all the retention measures included and one after removal of all retention measures (the "reference situation", see legend). After removing all retention measures from the model it appears that the effect of all measures combined is a change of approximately -45 cm in maximum water levels. In the remainder, the model without retention measures will serve as our base situation on top of which we will superimpose flood level effects of the individual retention measures. The model with all measures included serves as validation case ("All measures included").

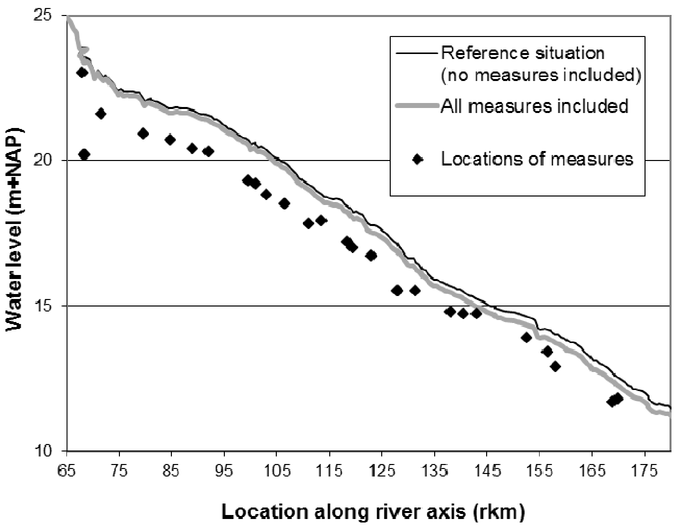

Figure 3. Calculated water levels along a section of the Meuse River with and without employment of flood mitigation measures (using the 250yr-discharge wave for a future climate scenario). Locations and inflow heights of retention measures are also indicated.

3.1 *Simple superposition (SS) of water level effects*

First, we investigate the accuracy of estimated combined flood impacts if we add together water level effects of the individual 38 retention measures, i.e. if we apply the simple superposition method (SS) as implemented in the Planning Kit PKB (but without using the constant reduction factor of 0.5). For this purpose, we apply the available 1-dimensional Meuse river model to each measure separately and, after adding effects of all individual measures together, compare the outcome to the model result where all measures were combined in one modelling run (the "validation case"). As inflow boundary the 250yr design flood wave is used (for future climate scenario, see thick line in Figure 4).

3.2 *Application of corrected-discharge method (CDM)*

As mentioned in Section 2.2, to apply the corrected discharge method it is required that for a range of discharge-values the water level effects for each separate measure are known. In section 3 we found out that all the measures combined yield a water level effect of approximately 45 cm, which in the reference situation is roughly equivalent to a discharge decrease of about 450 m^3/s in the design flood wave peak. Therefore, we choose as discharge range for our corrected discharge method a range that covers at least this 450 m^3/s difference: modifying the reference flood wave from -700 m^3/s to +100 m^3/s. Next, within this discharge-range we carry out flow simulations for the reference situation (no measure included) and for each individual measure (reference + 1 measure) at discharge intervals of 100 m^3/s. This gives per measure a hydrodynamic simulation at nine different discharge events, using the design flood wave modified by -700 m^3/s, -600 m^3/s, …, +100 m^3/s. A total number of 38 measures and one reference case for nine discharge events leads to a total of (38+1)*9 = 351 simulations to fill the database for the corrected discharge method. Water levels at intermediate discharges will be calculated by linear interpolation.

Of particular interest in the corrected-discharge algorithm is the required number of discharge steps to get acceptable results for the interpolated water levels. As mentioned earlier, we chose steps of 100 m^3/s, but we have also looked into the results if a step-size to 200 m^3/s were used (see Section 4). Another important issue is how to modify the design discharge wave for the simulations with lower or higher river discharges. One option is to subtract (or add) a constant discharge difference across the entire wave, effectively down- or upscaling the wave. Alternatively, for lowering the peak of the design discharge wave, one could flatten the peak of the wave by "topping off" at the desired peak value. Figure 4 demonstrates these two distinct approaches, which are both applied in this study.

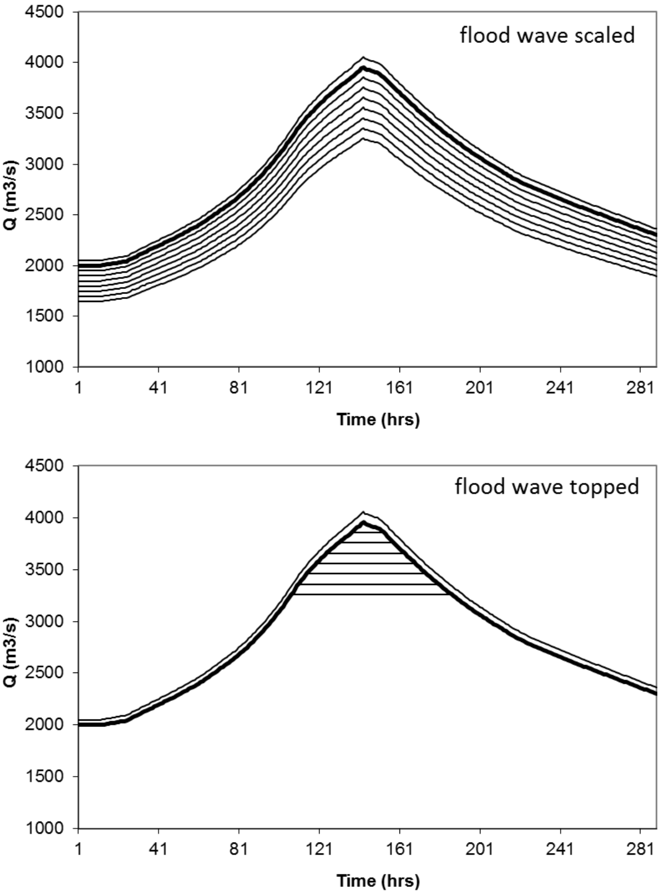

Figure 4. Modified discharge waves to fill the database for the CDM (peak values are 100 m^3/s apart, going from -700 m^3/s to +100 m^3/s). The reference flood wave (thick line) is the design 250yr flood wave (future climate scenario with +20% peak value of 3950 m^3/s). Top graph: using scaled waves, bottom graph: using "topped" waves.

4 RESULTS

In this section the results are presented of the application of the simple superposition method (SS) and of the application of the newly proposed corrected discharge method (CDM), used to estimate the combined flood level lowering effect of 38 retention measures along the Meuse River. Figure 5 shows the results for both methods. It shows that the traditional way of adding effects by SS gives a maximum error of -8.1 cm in estimated overall flood impact, with an average error of -4.2 cm (along the river axis). The negative values of these errors indicate that the SS method leads to *overestimated* flood impacts. Using the CDM still overestimates the combined flood level impacts, but the largest errors have now reduced to -4.0 cm, with an average error of -0.4 cm.

The convergence of corrected discharge values for each measure in the CDM are shown in Figure 6, showing that about four iterations of the CDM-algorithm (Section 2.2) were needed to obtain a stable end result. For the different retention measures the discharge corrections converged to values between -80 and -420 m^3/s (see Figure 6), signifying that in the CDM the effective flood impacts per measure correspond to river discharge-events that, in the reference situation, were 80 to 420 m^3/s lower than the 250yr design wave of peak 3950 m^3/s (see dQ-values in Figure 6). These results for the CDM shown in Figure 5 and Figure 6 were obtained by interpolating flood effects of the separate measures using the modified discharge waves shown in the top graph of Figure 4. These are the so-called “scaled” waves that differed from the used 250yr-wave by steps of 100 m^3/s.

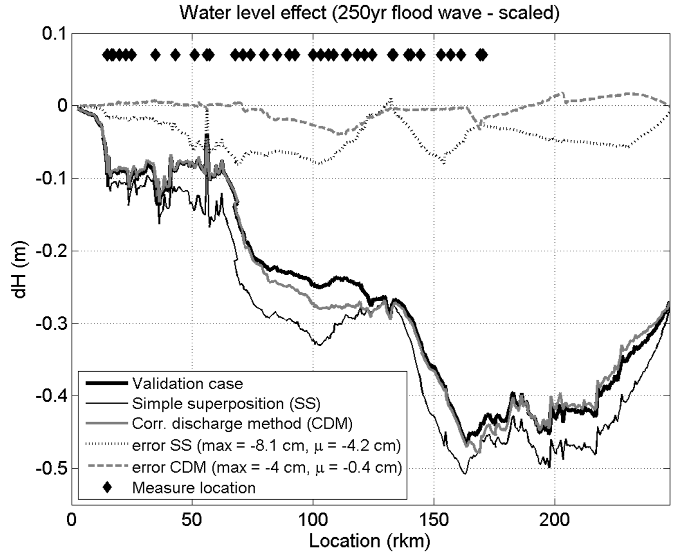

Figure 5. Calculated combined water level effects of 38 measures along the Meuse River for a future 250yr flood, using the simple superposition method (SS) and the corrected discharge method (CDM). In the validation case all measures were included in one single simulation run. Locations of measures are also indicated.

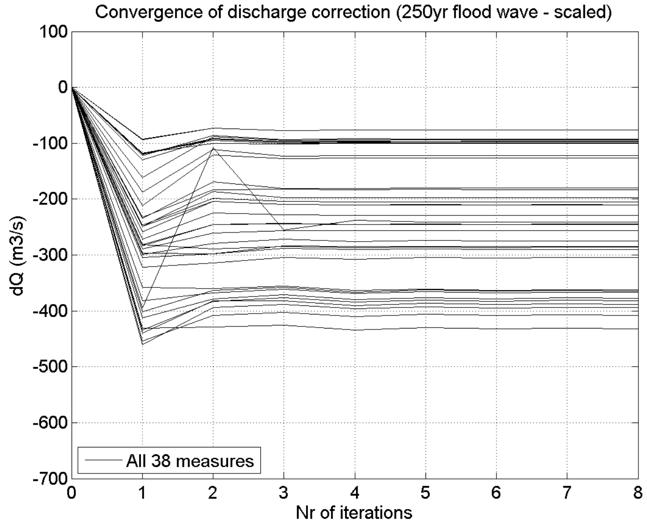

Figure 6. Convergence of discharge corrections dQ in the corrected discharge method (CDM) corresponding to results in Figure 5, using the scaled waves in Figure 4.

Using fewer simulations with modified discharge waves, for example by using steps of 200 m^3/s between the waves in Figure 4 (top graph), would require less effort in filling a database of flood effects for the CDM, but also gives larger interpolation errors for calculating corrected discharge values per measure (and for calculating corresponding corrected flood level impacts dH_i). In Figure 7 results are shown if using steps of 200 m^3/s between discharge waves, showing that more iterations are needed to reach a converged solution (now about 8 iterations are needed). Also, the match with the validation case is slightly poorer as compared to results in Figure 5. Using a step size of 200 m^3/s gives a maximum error of -4.3 cm with average error of -0.8 cm (results not shown here).

Alternatively, for calculating the dH_i-values per measure, one could use modified discharge waves that are topped off near the peak of the wave as shown in the bottom graph of Figure 4. This method of modifying the flood waves seems more representative of the actual effect that neighboring retention measures may have on a passing flood wave. The results of using these topped-off waves as basis in the CDM are shown in Figure 8. It shows that errors as compared with the validation case have now further reduced, giving only a maximum error in water level effects of 1.5 cm. This is a 81% reduction in error as compared to the simple superposition method (SS), where the maximum error was 8.1 cm. The average error over the entire trajectory of 250 km has also drastically reduced from -4.2 cm to -0.2 cm (95% error reduction). These stable end results for the case with topped-off waves were reached after 4 iterations with the CDM-algorithm (similar to convergence in Figure 6, results not shown here).

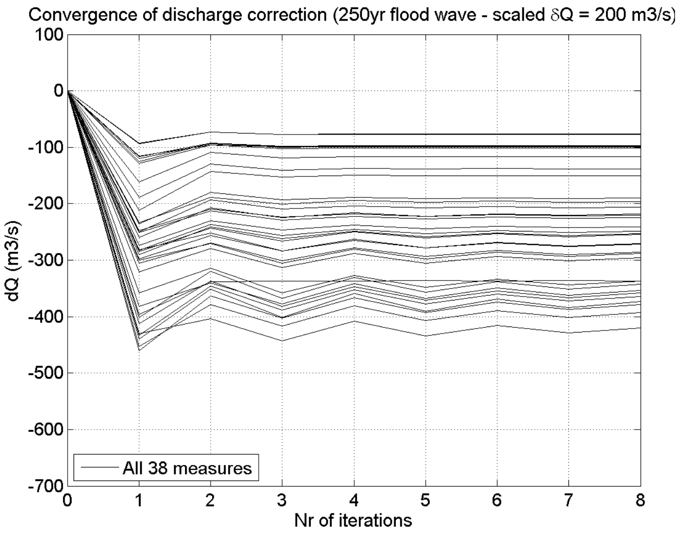

Figure 7. Convergence of discharge corrections if scaled waves have peak values 200 m^3/s apart.

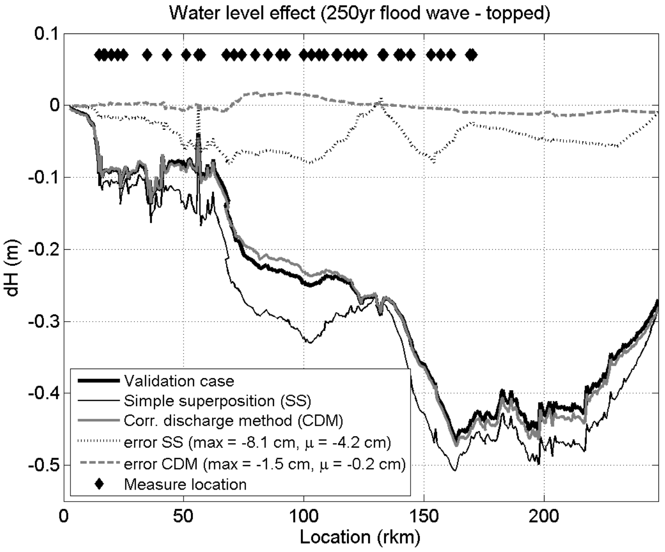

Figure 8. Results as in Figure 5, but now using topped-off waves in the CDM as opposed to scaled waves (see Figure 4).

5 DISCUSSION

In the current work we proposed a new method to estimate the combined flood level impact of several mutually interacting retention measures. In the considered case for the Meuse River it showed that maximum errors in estimated flood level impact could be reduced by 80% or more. It is expected that this improvement in estimation-accuracy could be even larger if additional measures such as floodplain lowering or dike relocations were included in the overall flood risk reduction strategy. The additional measures would lower food levels over large river sections and consequently affect the functioning of retention areas. In the commonly applied simple superposition method (SS, as included in the Planning Kit PKB) such mutual interactions between measures are not taken into account, generally leading to overestimated combined food-level-lowering effects. In the corrected-discharge method (CDM) these interactions are accounted for by associating modified flood level effects to each individual measure based on corrected-discharge events. These corrected discharge events mimic the influence of neighboring measures. It was shown that modelling choices relating to how these discharge events should be modified (e.g. how to modify the shape of the flood wave: see Figure 4) can have important impacts on the estimation-accuracy of the CDM. The importance of these modelling choices can be understood by realizing that, in reality, neighboring flood mitigation measures may affect peak water levels *and* the shape of the flood wave. Retention measures generally tend to flatten the peak of the flood wave, therefore it is not surprising that in the current study the approach of using “topped-off waves” was more successful than using the scaled waves (compare CDM-results between Figure 5 and Figure 8).

Other important choices in the application of the CDM are (i) where to define the “representative *point* location” of a measure (X_i, see Section 2.2), i.e. the location where the combined effect of all other measures is evaluated and (ii) the step size of the interpolation procedure between corrected-discharge flood impacts. Relating to the choice of X_i, we chose the upstream boundary of each separate measure, which seemed appropriate as this is the location where potential inflow to the retention basin starts. However, one could also consider the downstream boundary of the measure’s inlet, giving more weight to the influence of downstream measures on the local water level. Additional investigations on the CDM should be performed to indicate which of these choices leads to more accurate overall flood level impacts.

Our results in Section 4 showed that the step size of the interpolation procedure is quite important. Smaller steps require less iterations and give more accurate results. However, in our case study where we considered steps of 100 m^3/s and 200 m^3/s, the improvement in accuracy by using only half the step size (and thus requiring a database of flood effects that is twice as large) only yielded a very small improvement in the accuracy of the estimated combined flood impact. A clear disadvantage of the proposed method is that it may require an extensive database of flood level impacts for all measures to be considered. To minimize the efforts in constructing such a database, it is important to have a good understanding of the required number of flood impact entries per measure in the CDM-database.

The key advantage of the CDM is that it allows quick and accurate estimates of combinations of flood mitigation measures, without having to carry out actual hydrodynamic flow simulations to investigate each combination. This advantage allows us to more easily search for suitable combinations of measures among a large number of options. Also, the proposed CDM could be used to optimize deployment of measures, for example if seeking appropriate inlet-heights for different interacting retention areas. For this purpose, one could extend the CDM by including multiple data sets for each measure that relate to different deployment settings (i.e. using different inlet-heights). Using an optimization algorithm in combination with the corrected discharge procedure could then indicate optimal combinations of measures and their respective design characteristics. Because of the rapid calculation procedure of CDM, such an optimization could potentially be applied in real time, when the question arises how to optimally deploy retention measures when facing a particular flood threat.

6 CONCLUSIONS

A new method is proposed to estimate the impact on flood levels as caused by a large number of flood mitigation measures. The so-called corrected-discharge method (CDM) requires filling of a data base of flood effects per measure, and then allows quick and accurate estimates of flood impacts of chosen combinations of measures. Estimated flood impacts based on the CDM have shown to be ~80% more accurate than estimates based on the simple superposition method (SS) that, for example, is implemented in Dutch decision support tool "Planning Kit PKB". Besides providing improvement to such tools that are used in early planning stages of river engineering programs, the proposed CDM could also be used under real-time flood threat situations by guiding optimal deployment of emergency retention areas.

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