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On the importance of discharge variability in the morphodynamic modeling of rivers

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ABSTRACT: A 2D morphodynamic river model is applied to evaluate bed level changes after implementation of a flood prevention measure. The bed level changes are calculated in a deterministic simulation using a simplified discharge hydrograph, as well as in a probabilistic approach where a set of variable, more realistic discharge time-series is used. It is demonstrated that variability in the discharge-hydrograph has important impacts on the resulting bed levels, and that by using a simplified hydrograph in the deterministic calculation relatively large uncertainties are associated with the morphological outcomes. Recommendations are given to construct an adjusted simplified hydrograph that may yield a better match with probabilistic results, and thereby reducing uncertainties of deterministic morphodynamic calculations. Also, it is shown that morphological effects caused by a flood prevention measure may vary significantly laterally across a river section. This observation reinforces the need for a 2D approach in the evaluation of morphodynamic effects of river interventions.

Keywords: Morphodynamic modeling, River Rhine, Probabilistic analysis, Monte Carlo simulation

1 INTRODUCTION

Nowadays, morphodynamic models of rivers are becoming a more common tool in a variety of engineering and scientific studies. Examples are the studies by Verhaar et al. (2008), who investigated the morphological response to short term climate change, and van Vuren (2005), who used a morphodynamic model to study impacts on navigation requirements. On river reach scales, these studies mostly rely on 1-dimensional treatment of the hydrodynamics and the morphological response. These models give indications of the reach-averaged magnitudes of sediment transport quantities and erosion and sedimentation rates. However, whenever local sedimentation processes become relevant, such as pool or bar formation, 1D models can no longer describe the desired level of detail and 2D models become a necessity. Also, in case that intervention measures in a river occur only on one side of the river channel or if the river is strongly meandering, a realistic view on morphodynamic effects may only be achieved by utilizing 2-D morphodynamic models (e.g. Vasquez et al. 2008, Formann et al. 2007). In the Netherlands, such 2D models are now becoming an integral part of impact assessments of river engineering works, such that flood protection objectives are fulfilled while guaranteeing the required navigability conditions (Havinga et al., 2009).

In morphodynamic models, subroutines are included that link water flow to sediment transport. As a result of the calculated sediment transport, the bed levels are adjusted such that the total amount of bed material in the system is conserved. Sediment load varies strongly with river discharge. Therefore, long-term morphological changes can only be simulated realistically if a representative range of discharges is used in the calculations. For this purpose, commonly a simplified discharge hydrograph is defined. That way, the total amount of discharge levels is kept limited, which reduces the overall calculation time.

In the current study we investigate the reliability of using a simplified discharge hydrograph in 2D morphodynamic calculations. Does such a simplified hydrograph lead to representative bed level changes? To answer this question, we compare the results of a morphodynamic calculation using a simplified discharge-hydrograph with results from Monte Carlo simulations that are based on more realistic discharge time-series.

2 METHODOLOGY

The methodology in the current study involves a 2D-morphodynamic model of a river reach in the Netherlands. The model is used in a deterministic as well as in a probabilistic calculation procedure. In the deterministic procedure, a single calculation is carried out using a simplified representative discharge hydrograph as upstream boundary. In the probabilistic procedure a set of 55 calculations is carried out using more realistic discharge time-series. In the following sections the characteristics of the model and the calculation procedures are explained in further detail.

2.1 *The morphodynamic model*

A 2D morphodynamic model of the river Rhine is used, which is implemented in the software package Delft3D (see Lesser et al., 2004, Yossef et al., 2008). The model incorporates complex time-dependent multi-dimensional phenomena, such as curvature-induced point bar and pool patterns in bends. Impact assessment is possible at the small and intermediate spatial scales (in the order of hectometers and kilometers). Main limitations at this moment are proper simulation of the morphodynamic response in the near bank region and proper simulation of sediment exchange between the floodplain and low water bed (Havinga et al., 2005).

At the upstream boundary of the model a discharge time-series is imposed as a hydraulic boundary condition. In the calibration procedure of the model (see Sloff et al. 2006 and Yossef et al., 2007), this representative discharge hydrograph was used while adjusting model parameters until an acceptable match was achieved with average bed level changes, sediment loads and bed disturbances that were measured in the field. The main calibration parameter is the D_{50} grain size distribution of bed material. Figure 1 shows the D_{50}-values obtained in the field as compared with the calibration result. Table 1 gives an overview of the morphodynamic response of the model after calibration (sediment loads, annual bed level changes and celerity of bed disturbances).

Table 1. Model validation (morphodynamic response)

Quantity	Unit	Measured	Model
Sed. load upstream	$10^4\ m^3/yr$	6 - 9.5*	7.5
Sed. load downstream	$10^4\ m^3/yr$	8 - 11.5*	8.8
Bed level change	cm/yr	-2.5§	-3
Bed disturbances	km/yr	0.96§	1.1

* Ten Brinke et al. (2001)
§ Measurements by Rijkswaterstaat 1990-2005 (e.g. Sieben 2005)

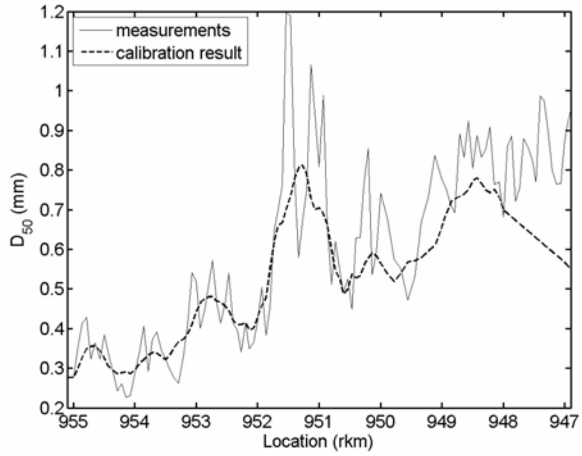

Figure 1. Measured mean grain size of bed material and the calibration result of the morphodynamic model.

2.2 *Representative hydrograph*

A simplified representative discharge hydrograph is constructed from measured discharge time-series between 1990 and 2000 (see Figure 2). In this hydrograph five discharge levels are chosen such that their frequency of occurrence matches the probability density function of the measured discharge times-series. Also the discharge levels are distributed over a one-year time span such that typical high- and low-discharge periods are well represented. In Sloff et al. (2006) more details can be found on the derivation of the simplified representative discharge hydrograph.

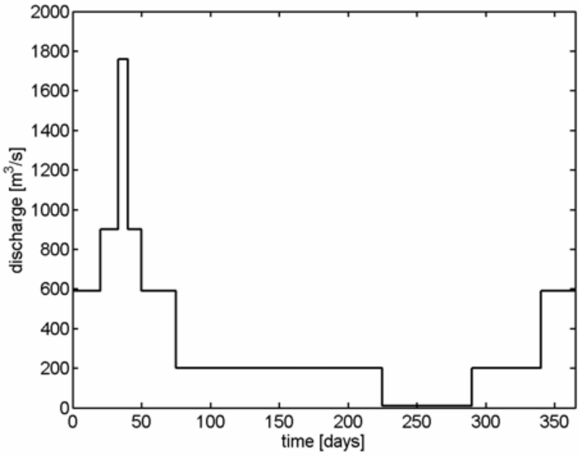

Figure 2. The representative discharge hydrograph that is used in the deterministic morphodynamic calculation.

2.3 *Deterministic vs. probabilistic approach*

The morphodynamic Rhine model is affected by various uncertainties, including those in the model schematisation and in the specification of the model input (for example boundary conditions, initial conditions) and the model parameters. Out of the various sources of uncertainty involved in the Rhine model, only the uncertainty in the discharge hydrograph imposed at the upstream boundary is considered. For this purpose, Monte Carlo simulation is utilised to quantify the ensuing uncertainty in the morphology. The outcomes of the Monte Carlo simulations (the *probabilistic approach*) will be compared to the outcome of the calculation using a simplified representative discharge hydrograph (Figure 2, the *deterministic approach*).

The principle of Monte Carlo simulation (Hammersly & Handscomb, 1964) is to run a deterministic model repeatedly, each time with a different set of model inputs. For each model run, a new discharge time series is constructed. On the basis of the set of outputs of all model simulations, the morphological response statistics are analysed in terms of the expected mean and percentile values that correspond with 1-σ and 2-σ deviations from the mean (e.g. percentile values of 2.3%, 15.9%, 84.1% and 97.7%). A sample size of 55 simulations is adopted for the probabilistic analysis.

2.4 *Synthesization of discharge series*

In the Monte Carlo simulation realistic discharge time-series are used as input. These discharge time-series are synthesized from discharge measurements between 1990 and 2000 by using the Nearest Neighbor methodology. In the Nearest Neighbor methodology a new time series is constructed by resampling from the original data set, while preserving the dependence structure of the original time-series (Lall & Sharma, 1996). The underlying concept is that resampling is restricted to the measured values that have similar characteristics as those of the latest selected value. One of these values, also known as Nearest-Neighbours, is selected at random and its successor is the next value to be added to the sequence.

In order to match the discharge time series with the numerical time step applied in the simulation, a conversion from daily discharges to discharges per interval of approximately 10 days is required. Therefore, the data is averaged over intervals of approximately 10 days, such that 36 of these intervals form a year (see Figure 3 for one of the synthesized 10-year time-series).

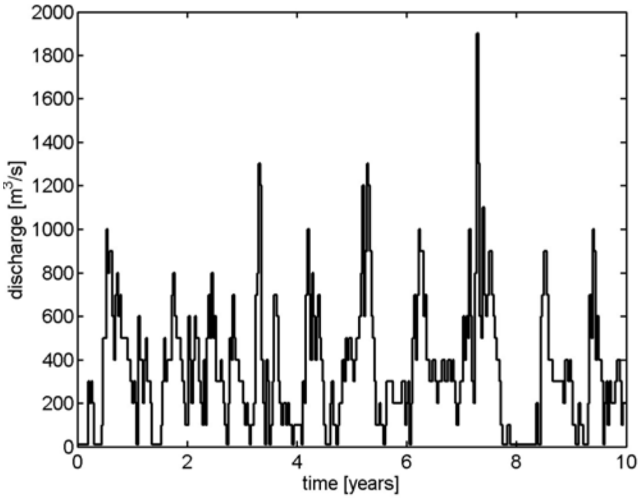

Figure 3. Synthesized discharge time-series.

2.5 *Selected case: a flood protection measure in the river Lek*

For the case study, a river widening measure, having the objective of flood protection along the river Lek is chosen. The Lek (which extends from the *Nederrijn*, i.e. the *lower Rhine*) is one of the Rhine branches in the Netherlands and carries roughly 20% of the Rhine-discharge that enters the Netherlands (see Figure 4). The chosen flood protection measure consists amongst others of widening the main channel towards the southern bank from 100 to 200 m (starting just downstream of location rkm 948 until rkm 951, see Figure 5). The widened part of the channel is separated from the main channel by a longitudinal dam containing several openings. In an earlier study, the impact of closing the openings step by step has been investigated (Van Vuren & Barneveld, 2008). Here, two openings in the dam are used, as illustrated in Figure 5. This means that on average only during 30 days a year discharge is conveyed through the channel behind the dam.

The bed level changes in the selected river reach will be evaluated after 10 years of morphodynamic evolution. For the deterministic case this means that the simplified hydrograph from Figure 1 is repeated 10 times in the calculation. In the Monte Carlo simulations, 55 different 10-year time series are being used (Figure 3).

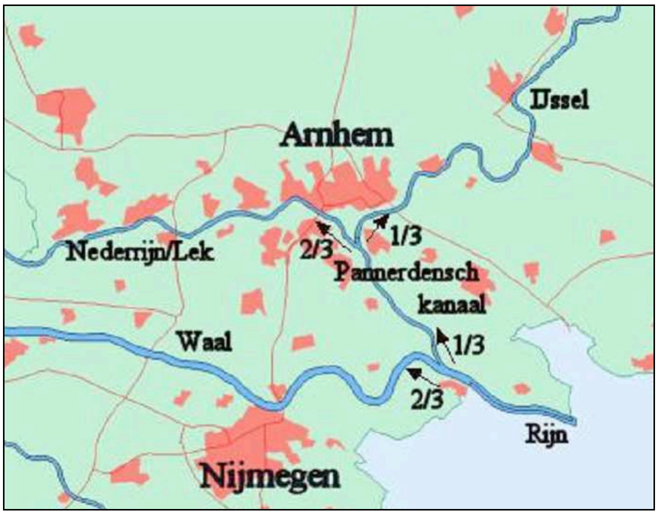

Figure 4: The Rhine branches in the Netherlands. At the bifurcation points estimates of the discharge distribution are given.

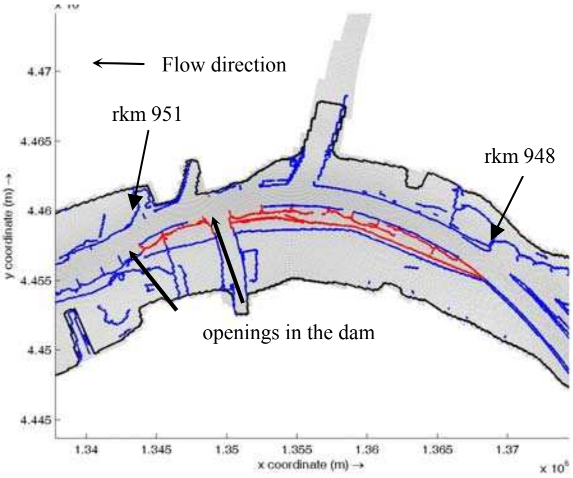

Figure 5: Case study area in the river Lek. The dam in the considered flood protection measure has 2 openings.

3 RESULTS

The results shown in this section all refer to effects that are obtained after 10 years of morphological simulation.

3.1 *Deterministic case*

Figure 6 shows the calculated bed level changes in the study area after 10 years of morphodynamic evolution, using the simplified discharge hydrograph (Figure 2). It can be seen that alongside the longitudinal dam (between rkm 948 and 951) regions of sedimentation occur (bed level rise) as well as regions where the bed is eroding. The strongest sedimentation is taking place between rkm 950 and rkm 951, near the locations where openings in the dam have been constructed. At these particular locations the flow field widens, causing flow velocities to decrease (in comparison to the reference situation) and sediment to settle down. Further upstream, the longitudinal dam in the flood protection measure keeps flow velocities similar to the reference situation. This is the case as long as the water level does not exceed the crest of the dam. Only when the longitudinal dam is overflown (on average 30 days a year) widening of the flow field is taking place, resulting in lower flow velocities leading to local sediment deposition. Therefore, regarding morphodynamic processes alongside the longitudinal dam two situations can be discerned:

1. At low discharges (if the water level is below the crest of the dam) the flow field is kept similar to the reference situation. Depending on the exact location in the main channel, the bed level changes little (relatively weak sedimentation or erosion may take place).
2. At higher discharges (if the water level is above the crest of the dam) sedimentation occurs due to widening of the flow field.

The occurrence of the mentioned processes may give rise to a rather complex sequence of erosion and sedimentation events in the main channel. As can be seen in Figure 6 this may result in an asymmetrical bed level response laterally across the channel. This asymmetry may also be reinforced by the curvature of the channel.

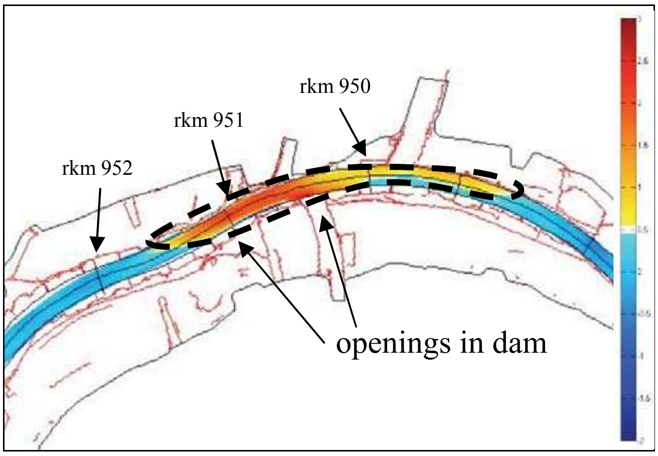

Figure 6. Bed level changes of the flood protection measure relative to the reference situation (deterministic case). The dashed contour line marks the region where sedimentation is taking place.

3.2 *Comparison of probabilistic results to deterministic case*

Because the variability of discharge events in relations to the crest height of the longitudinal dam leads to separate stages of erosion and deposition in the main channel, it is important that the morphodynamic impact by a range of possible discharge series is investigated. As described in section 2.4 55 time-series have been synthesized for this purpose. The resulting range of bed level changes is shown in Figure 7 (in the legend referred to as the *probabilistic* results). In this figure, the width-averaged bed level changes are depicted, showing the mean bed level change (thick black line), and the percentile values 2.3%, 15.9%, 84.1% and 97.7% (corresponding to 1-σ and 2-σ deviations from the mean). Also, in Figure 7 the width-averaged bed level change from the deterministic calculation is shown (gray line). The result from the deterministic calculation follows the probabilistic results quite well. However, at some locations it can be seen that the deterministic case exceeds the 2-σ boundary of bed level changes, which can be as much as 0.5 m above or below the mean value (e.g. at locations rkm 953.4 and 948.7).

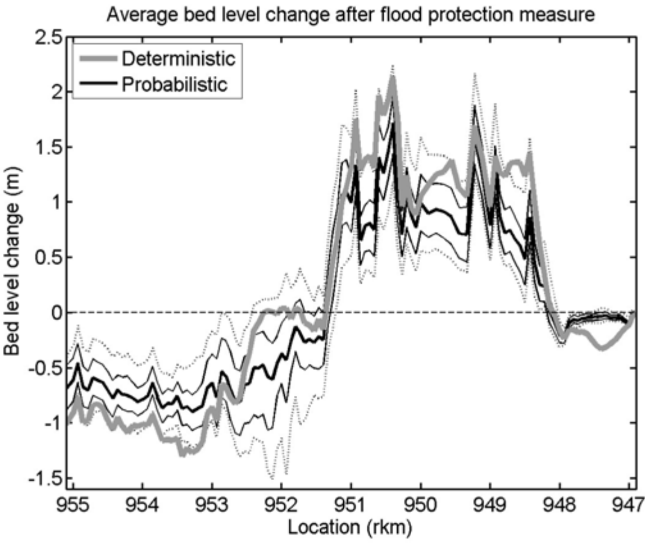

Figure 7. Differences in width-averaged bed level changes along the river axis (reference situation vs. flood protection measure).

To find out whether enough simulations have been performed to yield stable statistical outcomes, in Figure 8 the accumulated mean bed level changes and corresponding discharge deviations are shown. In this graph, two locations were selected for the analysis (locations rkm 950 and 952). It can be seen that for both locations the mean bed level changes converge rapidly and become stable after roughly 25 calculations. The standard deviation of bed level changes is more sensitive to individual events and thus converges at a lower rate. Nevertheless, also here a relatively stable 1-σ value is achieved after 55 calculations.

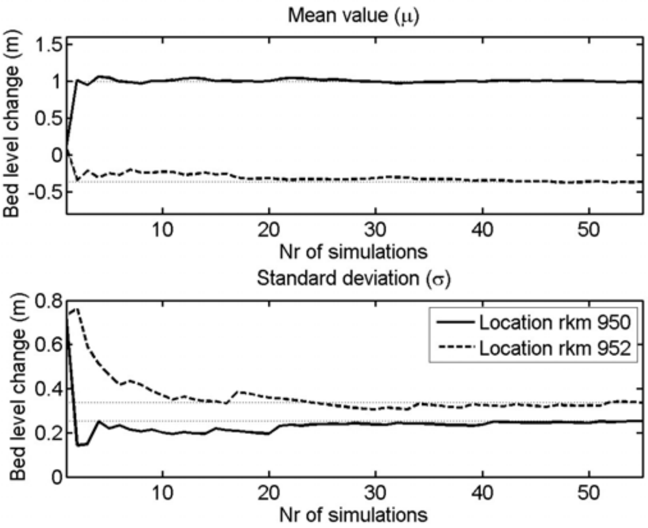

Figure 8. Convergence of statistical parameters with increasing number of simulations.

In section 3.1 it was pointed out that significant variability of bed level changes might occur laterally across the main channel. Therefore, in Figure 9 also bed level changes along three parallel longitudinal transects in the main channel are shown (along the northern bank, the center line of the main channel and along the southern bank). It can be seen that the morphological changes along the northern bank are similar to what is found in the center of the channel. At the southern bank, where the longitudinal dam was implemented, the morphological response is quite different. In all three cases, again, we see that the results from the deterministic case (gray line) fit the probabilistic results relatively well. However, also here it has to be emphasized that deterministic bed level changes may fall outside of the 2-σ boundaries of the probabilistic results and can easily be 0.5 m away from the mean values (of the probabilistic results).

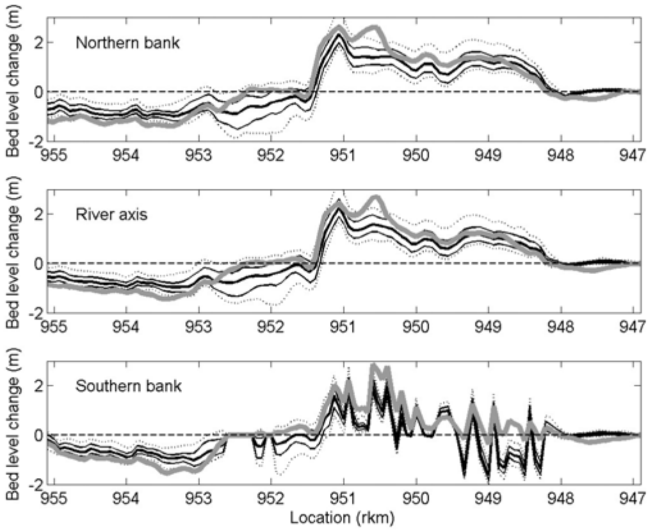

Figure 9. Bed level changes along the river axis (after flood protection measure).

4 DISCUSSION

In the current study it was shown that a deterministic morphodynamic simulation based on a representative discharge hydrograph can give different outcomes in comparison to a probabilistic analysis using more realistic discharge time-series. Therefore, if a simplified hydrograph is used (for example to reduce calculation time), one should be aware of the associated uncertainties in the model results. Here, bed level uncertainties were sometimes as large as 0.5 m. Alternatively, uncertainties related to a simplified hydrograph may be reduced if the hydrograph is adjusted to achieve a better match with probabilistic results. This practice may however have consequences for the calibrated model parameters. Some components of the morphodynamic model were originally calibrated using the representative discharge hydrograph, suggesting that the deterministic calculation with the representative hydrograph should yield ‘realistic’ outcomes. Therefore, the question arises how reliable the results are from the probabilistic approach if they clearly differ from the calibrated deterministic approach? Should the quality of the deterministic approach, and thus the quality of the calibration and the representative discharge hydrograph, be questioned? Or should the results of the probabilistic approach be questioned, since now model parameters are applied outside their calibration range? Ideally, the deterministic results fall well within the range of outcomes from the probabilistic approach such that this conflict does not exist.

Follow-up work will focus on this issue by trying to get a better match between probabilistic and deterministic calculations. Towards this objective, an iterative calibration procedure of model parameters will be followed, until results from the deterministic approach are in line with outcomes from the probabilistic approach. That way, a more representative discharge hydrograph may be obtained and the range of outcomes of the probabilistic results can be interpreted as uncertainty bounds to the deterministic calculation. An approach to achieve this could be as followed:

1. Calibrate (morphological) model parameters using a representative discharge hydrograph,
2. Use the calibrated model in a probabilistic approach and compare the obtained morphological results with the results obtained if using the representative hydrograph.
3. Adjust the representative hydrograph in the deterministic approach to achieve a better match with the probabilistic results.
4. Go back to step 1, using the new representative hydrograph (continue until the difference in step 2 is insignificant).

5 CONCLUSIONS

In the current study, a 2D morphodynamic river model was applied to evaluate the impact on bed level changes after implementation of a flood prevention measure. Bed level changes were calculated in a deterministic simulation using a simplified discharge hydrograph, and in a probabilistic approach where a set of more realistic discharge time-series was used. It was shown that discharge variability significantly affects the resulting bed levels, sometimes leading to bed level differences of 0.5 m or more between the deterministic and probabilistic approach. It is recommended that simplified discharge hydrographs be constructed in a way that a better match with (mean) probabilistic results are achieved. Also, the morphodynamic simulations showed that the bed level changes that result from the flood prevention measure vary significantly in lateral direction across the main channel. This observation reinforces the need for a 2D approach in the evaluation of morphodynamic effects of river interventions.

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