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Evaluation study: operational RWsOS Meren

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Summary

This study evaluates the performance of the D-HYDRO (Delft3D FM) hydrodynamic models during extreme storm events and the prolonged high water period that occurred in winter 2023-2024 in the IJsselmeer region (Netherlands) relative to observed measurements, and, in doing so, aims to create a baseline for model accuracy during high-water periods and increase understanding of model performance, strengths, and weaknesses.

The models analyzed are the updated D-HYDRO models from the operational RWsOS-Meren system, which is based on Delft-FEWS software. The study focuses on the performance of fine- and coarse-gridded D-HYDRO models with KNMI-HARMONIE meteorological forcing, namely *ijsselmeer4_harmonie*, *ijsselmeer4c_harmonie*, *markermeer4_harmonie*, *markermeer4c_harmonie*, and *veluwerandmeren4_harmonie*. For the *ijsselmeer4_harmonie* and *veluwerandmeren4_harmonie* models, archived operational model output from MATROOS archive is used. For other models, due to data availability issues, model results were re-created using archived meteorological forcing data.

The reforecasting results, however, were found to be closely aligned with operationally archived data, with a negligible RMSE difference (<0.8 cm), confirming the validity of the reforecasting approach for evaluating model performance.

Fine-gridded D-HYDRO models showed good accuracy during the studied period, with RMSE ranging from 2–4 cm at lake stations and around 5 cm at most riverine stations. Weighted average lake levels were predicted with a higher degree of accuracy (1–2 cm RMSE) due to the lake level correction ("meerpeilcorrectie") applied during modeling.

During Storm Pia (December 20th – 22nd, 2023) and Storm Henk (January 2nd – 5th, 2024), model performance deteriorated slightly, with RMSE increasing by 1-3 cm. Water level peaks were further underestimated, particularly during Storm Pia.

D-HYDRO models performed similarly to the older WAQUA models, with no significant improvement or decline in overall model performance. While differences in model performance can be considered negligible overall, performance does differ at specific stations (e.g. Kampen).

Coarse-gridded models showed reduced accuracy compared to their fine-gridded counterparts, particularly in riverine areas, where RMSE increases significantly (up to RMSE of 10–30 cm). This is in line with previous assessments. However, predictions of weighted average lake level and water levels at lake stations remain relatively unaffected, which means that coarse-gridded models continue to be useful for broader application in ensemble forecasting.

Therefore, we conclude that D-HYDRO models are sufficiently accurate for operational use under normal conditions, but also during extreme events, despite a slight reduction in model performance during those periods.

Contents

1 Introduction

1.1 Context

December 2023 to January 2024 was a period of high water in the IJsselmeer region of the Netherlands. This was due to a series of extreme storm events coinciding with prolonged high lake levels, caused by high amounts of precipitation across Europe from October to January. This study aims to evaluate the forecasting products that were available during those events to better understand the accuracy of the updated D-HYDRO (Delft3D FM) model set in the RWsOS Meren operational system relative to observed/measured parameters. The outcome of this study creates an updated baseline quality estimate for periods of extreme flood events and help to validate the applied operational procedure.

1.2 Study area

This study focuses on the Ijsselmeer region of the Netherlands, including the IJsselmeer, Markermeer, Veluwerandmeren, and the delta of the Ijssel and Overijsselse Vecht. Figure 1.1 presents a map of the study area, including locations of interest and approximate model domains.

Throughout this study, locations are grouped into three categories depending on their relative location in the system: lake, riverine, and transitional. Those are abbreviated as Lake, River, and R↔L, respectively. Section 2.1 describes the model domains and boundaries in more detail.

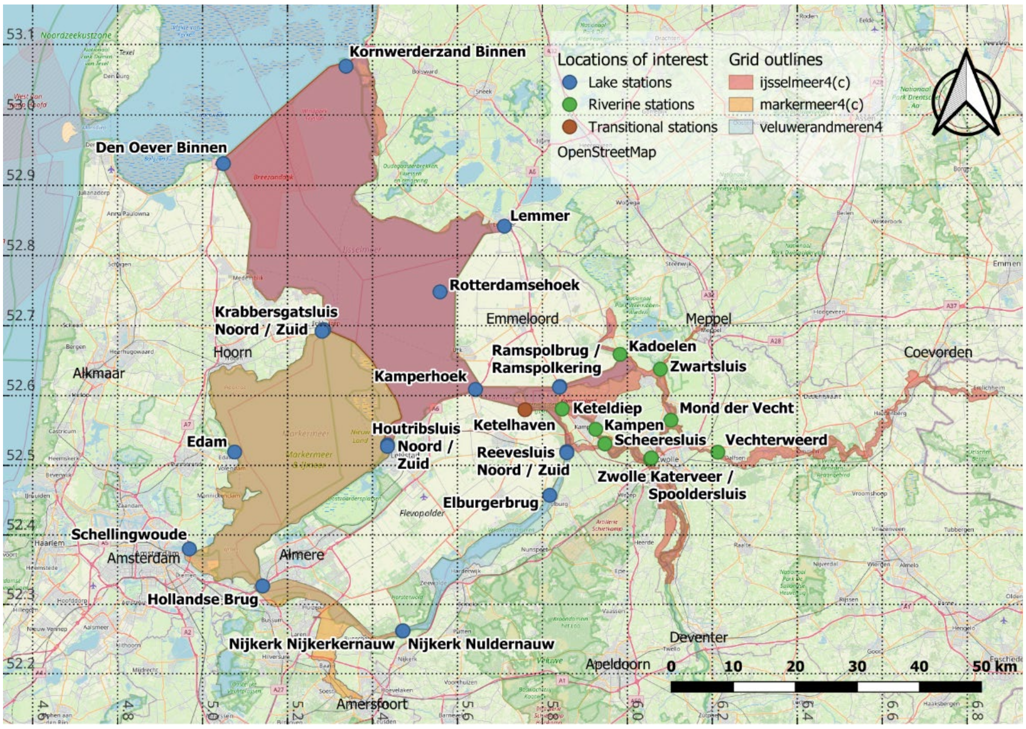

Figure 1.1 – Overview of the study area, locations of interest, and approximate model domains.

1.3 Reading guide

This report presents an overview of the statistical analysis, including the methodology, results, main conclusions. The information presented here assumes the reader is familiar with the study area and topic, but does not necessarily need to have expert knowledge about hydrodynamic modelling, the software used, or specific models considered in this study.

Chapter 2 describes the general approach and hydrodynamic models used in this study. Chapter 3 discusses the performance of the models using different scenarios and combinations of models. Chapter 4 presents overall conclusions.

2 Approach

This chapter presents a general overview of the methods used for this study. This includes a description of the models that were analysed, steps taken to recreate the operational dataset for the period of interest, as well as techniques used to assess model performance.

2.1 Description of models

The following sixth-generation (D-HYDRO) models were evaluated in this study:

- *ijsselmeer4* (dflowfm2d-ym_ijvd_rd-j19_6-v2a)
- *ijsselmeer4c* (dflowfm2d-ym_ijvd_100m-j19_6-v2b)
- *markermeer4* (dflowfm2d-markermeer-j19_6-v2a)
- *markermeer4c* (dflowfm2d-markermeer_100m-j19_6-v2a)
- *veluwerandmeren4* (dflowfm2d-veluwerandmeren-j19_6-v2a)

The D-HYDRO IJsselmeer and IJssel-Vecht delta (IJVD) model schematization with KNMI-Harmonie meteorological forcing (*ijsselmeer4*; Menno Genseberger et al., 2020) covers the area encompassed by the IJsselmeer and the delta of the Overijsselse Vecht and IJssel.

The model domain (Figure 1.1) connects to the Wadden Sea near the Afsluitdijk, via the Stevin sluices at Den Oever and the Lorentz sluices at Kornwerderzand. It also connects to the Markermeer near the Houtribdijk, via the Krabbersgat sluices at Enkhuizen and the Houtrib sluices at Lelystad, as well as Drontermeer near the Reevesluis and the Reevediep bypass. At the upstream boundary, the model is limited by the Rhine branches running between Ketelmeer and Reevediep, as well as those at the Overijsselse Vecht.

Figure 2.1 – Grid overview of D-HYDRO ijsselmeer4 model.

The upstream boundaries are forced with discharges and water levels at Olst and Ommen, similar to the fifth-generation WAQUA IJsselmeer IJVD model. The downstream boundary is forced with water levels at Den Oever and Kornwerderzand buiten. It also depends on the number of open sluice gates and target water level from IJG-ABT RWsOS-IWP system.

The existing *ijsselmeer4* model domain covers the IJsselmeer, Ketelmeer, and Zwartemeer and parts of the Overijsselse Vecht and IJssel. The model domain is schematized with irregular triangular grid consisting of 849,344 elements and 658,555 nodes, making it a relatively large D-HYDRO model (Figure 2.1).

The sixth-generation model schematizations of *markermeer4* and *veluwerandmeren4* (Menno Genseberger et al., 2017) cover the Markermeer, IJmeer, Gooimeer, Eemmeer, Eem, Nijkerkernauw, Nuldernauw, Wolderwijd, Veluwemeer, and Drontermeer areas (Figure 1.1). The model has boundaries with the IJ at the three Oranjesluizen and the Prins Willem Alexandersluis, the Vossemeer at the Roggebotsluis, and the IJsselmeer at the Houtribdijk (which includes the Krabbersgatsluizen at Enkhuizen and the Houtribsluizen at Lelystad). At the latter boundary, the *markermeer4* grid aligns with that of the *ijsselmeer4* model.

The grid for *markermeer4* model is characterized by a gradual transition between grid cells with 50 m resolution at the edge to 400 m in the middle of Markermeer, boundary-fitted computational grid outline, and a higher resolution of up to 20 m near features such as the Marker Wadden (Figure 2.2). A similar pattern holds for the *veluwerandmeren4* model, where the grid resolution varies between 5 and 50 m across the domain.

The triangular D-Flow FM grid for *markermeer4* includes 345,634 elements and 175,582 nodes. The grid for *veluwerandmeren4* contains 90,974 elements and 46,507 nodes. In comparison, the curvilinear 5th generation WAQUA grid for Markermeer had 109,793 elements, while the Veluwerandmeren grid had 64,616 elements.

Figure 2.2 – Grid overview of D-HYDRO markermeer4 and veluwerandmeren4 models.

Further developments were implemented to enhance the performance of the models in the years after initial implementation. A detailed description of those changes can be found in Carlijn Eijsberg-Bak et al., 2022, and Menno Genseberger, 2021.

One such development was to create D-HYDRO models with a coarser grid than the *ijsselmeer4* and *markermeer4* models. These coarse-gridded models (*ijsselmeer4c* and *markermeer4c*) have reduced computation times, which enables ensemble forecasting for uncertainty estimation.

For both the *ijsselmeer4c* and *markermeer4c* models, a uniform computational grid with square cells of 100 m by 100 m was adopted for the large lake areas (Menno Genseberger et al., 2022 and Menno Genseberger, 2022, respectively). For the *ijsselmeer4c* model, the square grid is coupled with a primarily curvilinear grid eastwards of Ketelbrug, because the 100-meter resolution is too coarse to properly represent the narrow waters of the IJssel-Vecht delta.

The following fifth generation (WAQUA) models were also evaluated in this study:
- *ijsselmeer3 (simona-ym_ijvd_ov-j16_5-v1)*
- *markermeer3 (simona-mm-j10_5-v1)*

The WAQUA models, which cover approximately the same domain as the D-HYDRO models, were studied to assess the differences in performance between the fifth- and sixth generation models. The outcome of this comparison determines whether WAQUA models have any added value compared to the currently operational sixth-generation D-HYDRO models.

WAQUA models were predecessors of the sixth-generation model set implemented in D-HYDRO. The spatial coverage and main principles of the WAQUA models are similar to those described above for the D-HYDRO models, with differences around the Reevediep bypass. More detailed information is available in Carlijn Bak-Eijsberg et al., 2015.

Both D-HYDRO and WAQUA models were run with HARMONIE meteorological forcing, thus making the model-meteorology combination reference names for this study:
- *ijsselmeer4_harmonie* and *ijsselmeer4c_harmonie;*
- *markermeer4_harmonie* and *markermeer4c_harmonie;*
- *veluwerandmeren4_harmonie;*
- *ijsselmeer3_harmonie* and *markermeer3_harmonie*.

2.2 Reforecasting procedure

Model results for the period from December 2023 through January 2024 are available in the RWS Production MATROOS archive for two models (*ijsselmeer4_harmonie* and *veluwerandmeren4_harmonie*). For these two models, performance analysis was done using model results directly from the archive.

However, archived model results are not available for the other models due to operational storage issue that have only recently been resolved. Instead, data for the period of interest were re-created using archived forcing data to run the model train for several subsequent forecasting cycles, mimicking the operational system. This pseudo-operational “reforecasting” procedure replicates the operational model train with 6-hour hindcast runs combined with a subsequent 6-hour forecast run. The analysis in this study was based solely on the hindcast results of those runs. A short forecast run was included solely for the sake of applying “*meerpeilcorrectie*” (lake level correction) to the hindcast results, which requires a minimum of 6 hours of forecast data.

The general modelling approach was the same for operational and reforecasted models, including model configuration, computational facilities, and procedure. Considering this, the main difference between operational and reforecasted model runs is in the boundary conditions at laterals along the Overijsselse Vecht. Since forecasts for some of the laterals are not archived in MATROOS, these were replaced with measurement data where available. The measurement discharge series were used at Sallandse Wetering, Gemaal Kloosterzijl, and Ommerkanaal (extended by FEWS-Vecht data). Hindcast data from FEWS-Vecht system was used at Kostverlorenzijl and Streukelerzijl. Additionally, where absolutely no data was available, the discharge at Regge Linderbeek was approximated as 4 times the discharge at Archem Linderbeek while discharge at Gemaal Cellemuiden was set to zero.

To check whether the differences in boundary conditions significantly affect model performance, the operational and reforecasted model results were compared. Reforecasting was performed for both models with and without available operational model data in MATROOS. The purpose of the comparison between the two approaches is to ensure that the results of this study can be compared to outcomes of future verification studies that are based on operational data.

2.3 Statistical analysis

Modelled time series were compared to measurements (observations) available in the MATROOS archive for the period of interest, for both operational and reforecasted model results. The comparison of D-HYDRO and WAQUA results was done only for the two models for which modelled data were available in MATROOS.

Standard statistical metrics such as bias, standard error, and root mean square error (RMSE), were used to assess the performance of the models relative to observation data. In addition to these objective metrics, model performance was analysed qualitatively by visually comparing water level time series during the period of interest for all measurement stations.

Statistical bias is a systematic error that is observed when the assessed series is compared to another. In this study, the bias of modelled series with respect to measurements (observations) was computed, meaning that it represents the average value by which water level is over- or underestimated by the model at a specific location over a specific period.

Standard error of an estimated parameter is equal to its standard deviation from a reference series, and therefore is often referred to as standard deviation (STD). STD measures the dispersion of a dataset relative to its mean. When comparing two datasets, values of the estimated series are compared against the mean of the reference dataset. This parameter is computed on the unbiased series.

RMSE combines the notions of bias and standard error (deviation) by representing the differences on the biased series. Faced with alternative estimations for a given parameter, it is generally reasonable to use the one with the smallest RMSE.

In this study, observed (measured) values are considered objectively “true” values. This approach, however, does not consider measurement error or any other possible source of uncertainty in measurement data. In reality, statistical differences between modelled and measurement series are also influenced by the accuracy of measurement data, which may be reduced during extreme events.

The analysis was done for the period between October 1st, 2023 and February 1st, 2024, for the models with operational data available in MATROOS and between December 11th, 2023 and January 16th, 2024, for the reforecasted models. Both periods fully cover the lead up to and aftermath of Storm Pia (December 20th – 22nd, 2023) and Storm Henk (January 2nd – 5th, 2024). The longer period (starting on October 1st) also covers the period when water levels started to rise before the winter floods. To assess whether model performance is different during major storm events, each storm was also looked at individually by limiting the data to just before and after each event.

3 Results

3.1 Differences between operational and reforecasted model results

This section compares the model time series saved in the operational MATROOS database in December 2023 and January 2024 with the model time series generated later using the reforecasting procedure described in Section 2.2. The comparison is done for the two models for which both datasets are available (*ijsselmeer4_harmonie* and *veluwerandmeren4_harmonie*). It should be noted that not all locations within the two mentioned models had data available in MATROOS. Therefore, locations with missing data are not represented in this comparison (Katerveer, Ramspolkering Ketelmeerzijde, Rotterdamsehoek, Scheeresluis, Schellingwoude, Spooldersluis, Vechterweerd, Zwartsluis).

Differences in performance (as represented by RMSE difference) between operational and reforecasted models are relatively small (up to 0.3 cm) and limited to certain areas (Figure 3.1, Table 3.1). The stations with the most pronounced differences (though still limited to 0.6 – 0.8 cm RMSE) are the ones located along rivers and most likely affected by the change in boundary conditions along the Vecht (Kadoelen, Mond der Vecht), as described in Section 2.2.

Table 3.1. Difference in accuracy of water level time series between operational and reforecasted models (December 11, 2023 – January 16, 2024).

Name	Model	Position	Δ_{Bias}, cm*	Δ_{STD}, cm*	Δ_{RMSE}, cm*
Den Oever binnen	IJS	Lake	0.0	0.0	0.0
Elburgerbrug	VRM	Lake	0.0	-0.1	-0.1
Houtribsluizen noord	IJS	Lake	-0.1	-0.1	-0.2
Kadoelen	IJS	River	0.6	-0.3	0.2
Kampen	IJS	River	-0.2	-0.4	-0.2
Kamperhoek	IJS	Lake	-0.1	-0.2	-0.2
Keteldiep	IJS	River	-0.1	-0.3	-0.3
Ketelhaven	IJS	R ⇔ L	-0.1	-0.3	-0.2
Kornwerderzand binnen	IJS	Lake	0.0	-0.1	-0.2
Krabbersgatsluis noord	IJS	Lake	-0.1	-0.1	0.0
Lemmer	IJS	Lake	-0.1	0.0	-0.1
Mond der Vecht	IJS	River	0.8	0.4	0.7
Nijkerk Nuldernauw	VRM	Lake	0.0	0.0	0.0
Ramspolbrug	IJS	Lake	0.3	-0.3	-0.1
Reevesluis noord	IJS	Lake	-0.1	-0.2	-0.3
Reevesluis zuid	VRM	Lake	-0.1	-0.1	-0.1
IJsselmeer (lake)			-0.1	-0.1	-0.1
Veluwerandmeren (lake)			-0.1	-0.1	-0.1
Average			0.0	-0.1	-0.1

**Negative Δ values represent higher reforecasted model metrics as compared to metrics of archived data from operational models.*

A similar pattern is observed for the other two statistical metrics, bias and STD (Table 3.1). The statistical metrics for all stations located on the lakeshore or in sluices connecting lakes differ between operational and reforecasted approaches by no more than 0.3 cm. Despite the differences in boundary conditions imposed on riverine stations (especially at Kadoelen and

Mond der Vecht), the average STD and RMSE in reforecasted runs decreases only slightly, while bias is, on average, the same. The accuracy of weighted lake levels does not vary significantly in both cases, as all statistical metrics change only by 0.1 cm.

Overall, the differences between model performance statistics obtained operationally and through the reforecasting procedure are negligible. Therefore, this study can be considered to provide a representative evaluation of operational model performance.

Overall, this study uses operationally archived data where they are available for specific models and locations. All other model/location combinations are analysed using data generated through reforecasting.

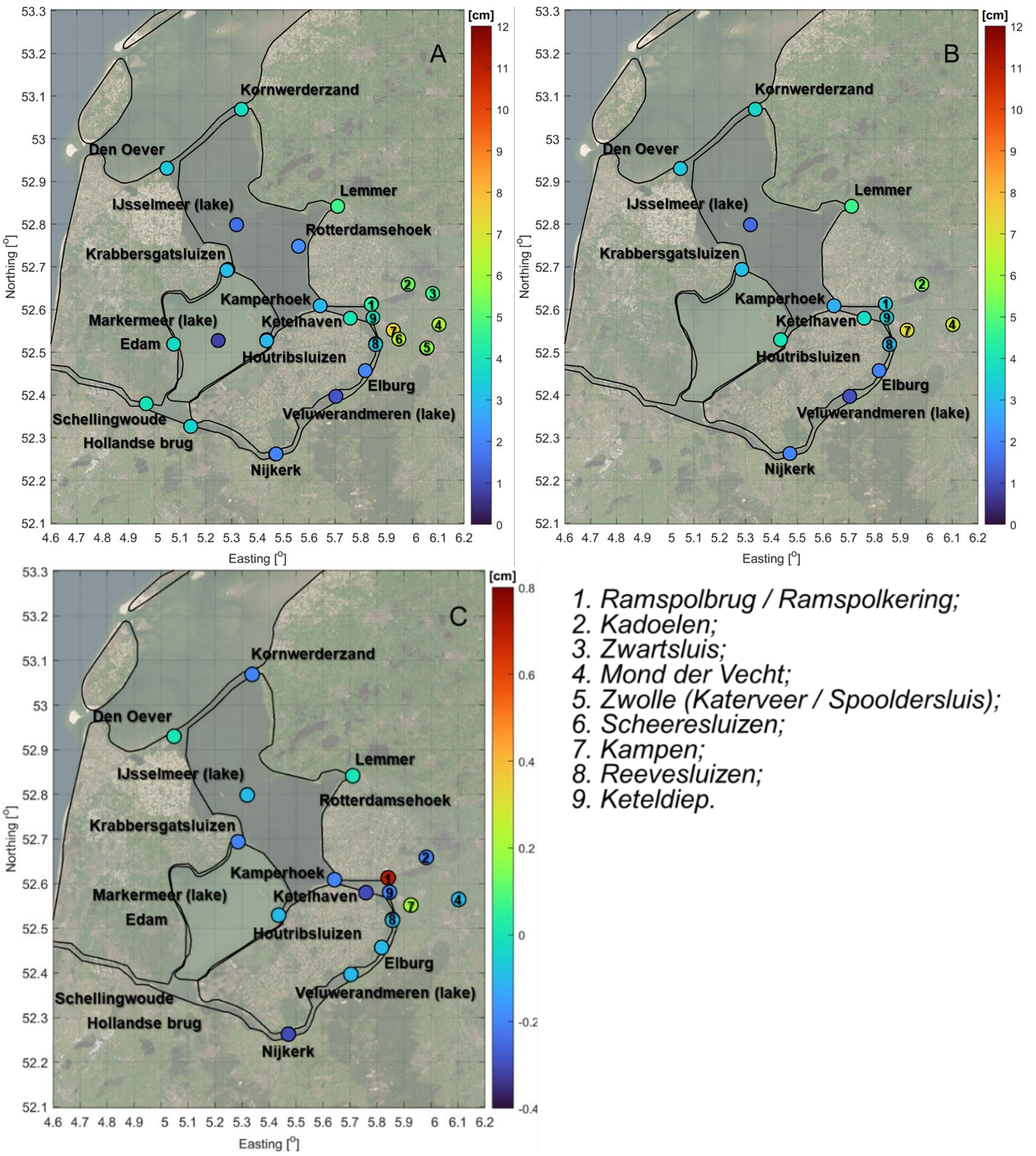

Figure 3.1 – RMSE of water level values simulated by RWsOS-Meren fine-gridded D-HYDRO models in reforecast (A) and operational (B) mode, and difference between RMSE of those modes (C) for the period December 11, 2023 to January 16, 2024.

3.2 Fine-gridded model performance

This section presents the model performance results for fine-gridded models. The *ijsselmeer4_harmonie*, *markermeer4_harmonie* and *veluwerandmeren4_harmonie* models are described in Section 2.1.

3.2.1 Compared to measurement data during full study period

Figure 3.1 shows a map of model performance in terms of RMSE in water level relative to observations, and Table 3.2 provides this information in tabular form. The performance of the fine models varies slightly by location but overall is approximately 2 – 6 cm, except for two stations (Zwolle Katerveer and Vechterweerd).

Table 3.2. RWsOS-Meren fine-gridded D-HYDRO model performance – statistical metrics (in cm) (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias	STD	RMSE
Den Oever binnen	IJS	Lake	-0.7	3.2	3.3
Edam*	MRK	Lake	-3.1	2.1	3.7
Elburgerbrug	VRM	Lake	0.2	1.8	1.8
Hollandse brug	MRK	Lake	2.5	2.5	3.6
Houtribsluizen noord	IJS	Lake	0.7	3.8	3.9
Houtribsluizen zuid	MRK	Lake	1.6	2.5	3.0
Kadoelen	IJS	River	4.3	3.2	5.4
Kampen	IJS	River	-2.8	4.7	5.4
Kamperhoek	IJS	Lake	0.0	2.8	2.8
Katerveer	IJS	River	-14.1	10.0	17.3
Keteldiep	IJS	River	1.3	3.3	3.5
Ketelhaven	IJS	R ↔ L	1.6	3.4	3.8
Kornwerderzand binnen	IJS	Lake	-0.6	3.4	3.5
Krabbersgat noord	IJS	Lake	-1.2	2.9	3.1
Krabbersgat zuid	MRK	Lake	-1.1	2.9	3.1
Lemmer	IJS	Lake	1.0	4.4	4.5
Mond der Vecht	IJS	River	0.8	5.2	5.2
Nijkerk Nijkerkernauw	MRK	Lake	0.9	3.8	3.9
Nijkerk Nuldernauw	VRM	Lake	-0.3	2.0	2.0
Ramspolbrug	IJS	Lake	1.8	2.7	3.2
Ramspolkering Ketelmeerzijde	IJS	Lake	0.8	4.3	4.4
Reevesluis noord	IJS	Lake	1.3	4.8	4.9
Reevesluis zuid	VRM	Lake	1.7	2.4	3.0
Rotterdamsehoek	IJS	Lake	0.0	2.2	2.2
Scheeresluis beneden	IJS	River	1.2	6.2	6.4
Schellingwoude	MRK	Lake	1.7	3.5	3.9
Spooldersluis	IJS	River	-2.0	5.2	5.6
Vechterweerd	IJS	River	14.4	8.0	16.5
Zwartsluis	IJS	River	-0.2	4.7	4.7
IJsselmeer (lake)			0.1	1.5	1.5
Markermeer (lake)			-0.1	0.8	0.8
Veluwerandmeren (lake)			0.0	1.0	1.0
Average			0.5	3.1	3.4

**Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate from -3.1 to -0.1 cm and RMSE from 3.7 to 2.1 cm.*

Stations located directly on a lake or adjacent to sluices are more accurate, with an RMSE between 2 and 4 cm. Markermeer stations have slightly lower accuracies, with an RMSE closer to 3 - 4 cm. Several riverine stations and Lemmer have an RMSE above 5 cm.

STD displays a similar pattern to RMSE and varies between 2 to 6 cm across the entire study area, except for Katerveer and Vechterweerd. Riverine stations generally show a higher STD.

Bias varies between -3 to 4 cm (except for Zwolle Katerveer and Vechterweerd stations, which have a bias of -14 and 14 cm, respectively) and don't appear to be consistent in terms of magnitude or direction (+/-) (Table 3.2). The biases identified in this analysis could potentially be reduced by applying post-processing techniques on the modelling output, leading to more accurate forecasts. However, since the data produced during this study include substantial effects from extreme events and do not include seasonal variation, it would be preferable to use a significantly longer time period to determine true bias at each station. Given that the computed bias is not more that 10% of the spread in water level values (also considering enlarged bias due to effect of storms), it is not advised to apply any post-processing for bias to model outputs based on this study.

Simulated weighted lake levels deviate less, on average, from the values derived from observations because they are derived by averaging water levels from several locations. RMSE varies from 1 to 2 cm, while bias is virtually absent. Higher error values in the IJsselmeer lake level are due to there being more in- and outflow laterals in this lake compared to the other lakes. Some of these laterals are unknown. Considering this, and the greater variability in IJsselmeer weighted lake levels (-10 to 60 cm NAP), the accuracy of RWsOS models can be considered acceptable overall.

3.2.2 Compared to measurement data during Storm Pia

As explained in Section 2.3, the statistical analysis was done for the entire period of interest and for each storm individually. Table 3.3 presents the model performance at main locations during Storm Pia, which arrived in the Netherlands between December 20th and 22nd, 2023. Statistics for the full set of stations can be found in Appendix A.1.

Table 3.3. Performance metrics (in cm) of RWsOS-Meren fine-gridded D-HYDRO models at main stations during Storm Pia (December 19th through 25th, 2023).

Location	Model	Position	Bias	Δ_{full}*	STD	Δ_{full}*	RMSE	Δ_{full}*
Edam**	MRK	Lake	-3.2	*-0.1*	2.9	*0.8*	4.3	*0.6*
Elburgerbrug	VRM	Lake	-0.5	*-0.7*	2.0	*0.2*	2.1	*0.3*
Kampen	IJS	River	-4.4	*-1.6*	4.5	*-0.2*	6.3	*0.9*
Lemmer	IJS	Lake	0.1	*-0.9*	5.3	*0.9*	5.3	*0.8*
Ramspolbrug	IJS	Lake	0.1	*-1.7*	3.6	*0.9*	3.6	*0.4*
Zwartsluis	IJS	River	-5.4	*-5.2*	4.3	*-0.4*	6.8	*2.1*
IJsselmeer (lake)			-0.4	*-0.5*	1.9	*0.4*	1.9	*0.4*
Markermeer (lake)			-0.4	*-0.3*	0.7	*-0.1*	0.8	*0.0*
Veluwerandmeren (lake)			-0.7	*-0.7*	0.7	*-0.3*	1.0	*0.0*
Average			-0.6	*-1.1*	3.9	*0.8*	4.2	*0.8*

**Negative Δ values represent a decrease in the statistical metric (more negative or less positive) during Storm Pia as compared to the entire period (Dec 11th – Jan 16th).*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate from -3.2 to 0.2 cm and RMSE from 4.3 to 2.9 cm (Δfull = 0.8 cm).*

Model performance was analysed during the period between December 19th and 25th, 2023, to capture the run-up to and aftermath of the event. Performance clearly deteriorated during this period (Table 3.3). RMSE and STD increased for most of the stations, reflecting an increase in model uncertainty and deviation from the measurements. Riverine station showed the largest decrease in performance.

In most cases, the increase in STD of measured values during the storm is related not only to the effects of the extreme conditions but also to increased error in measurement data. However, the effect of the storm on measurement accuracy could not be assessed in this study.

Differences between simulated and observed values, however, are not only a result of the model set-up or measurement accuracy. Another source of uncertainty in water level predictions comes from the meteorological forcing data, which is especially important during extreme events.

The bias calculated for Storm Pia shifted towards negative values for all the studied locations, by 1 – 2 cm on average (Table 3.3). This means that water levels were underestimated during the event. Visually comparing the time series (Figure 3.2) shows a delayed prediction of peaks at certain stations during the event. The absolute values of model bias during Storm Pia might increase even further when considering only the period of the storm (i.e. excluding the lead-up and aftermath).

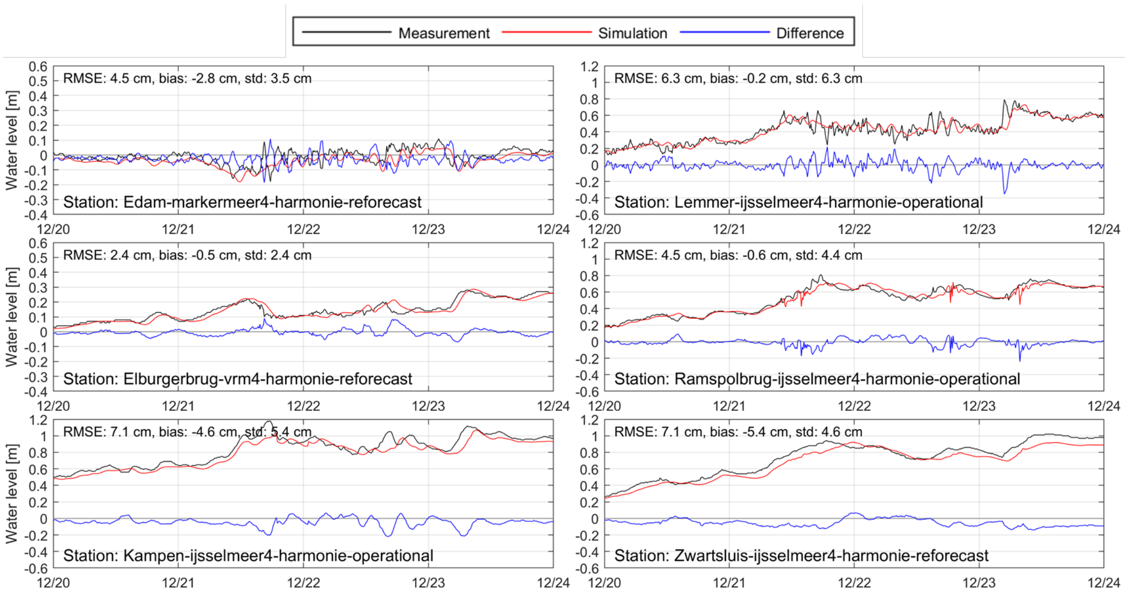

Figure 3.2 – Simulated (red) and observed (black) water levels during Storm Pia, and the difference between the two (blue).

3.2.3 Compared to measurement data during Storm Henk

Storm Henk arrived in the Netherlands between January 2nd – 5th, 2024. Statistics were computed for the period between December 31st, 2023, and January 6th, 2024. Compared to Storm Pia, the analysis for Storm Henk found reduced model performance for the main stations, as reflected by an increased STD and RMSE (Table 3.4). Average decrease in model performance over the full set of stations is similar for both storms Pia and Henk (Appendix A.1).

However, contrary to Storm Pia, bias changes during Storm Henk relative to the entire study period are not unidirectional and are in general smaller then during Storm Pia. This is especially visible when comparing weighted lake level metrics and average bias difference between the two storm events. This discrepancy may be due to Storm Henk's shorter duration and the fact it occurred during a stable period of high water (Figure 3.3), while Storm Pia occurred as water levels were rising (Figure 3.2).

Table 3.4. Performance metrics (in cm) of RWsOS-Meren fine-gridded D-HYDRO models at main stations before, during, and after Storm Henk (December 31st, 2023 through January 6th, 2024).

Location	Model	Position	Bias	Δ_{full}*	STD	Δ_{full}*	RMSE	Δ_{full}*
Edam**	MRK	Lake	-3.6	*-0.5*	2.5	*0.4*	4.4	*0.7*
Elburgerbrug	VRM	Lake	-0.5	*-0.7*	2.2	*0.4*	2.3	*0.5*
Kampen	IJS	River	-7.5	*-4.7*	3.6	*-1.1*	8.3	*2.9*
Lemmer	IJS	Lake	1.0	*0.0*	6.1	*1.7*	6.2	*1.7*
Ramspolbrug	IJS	Lake	1.7	*-0.1*	2.7	*0.0*	3.2	*0.0*
Zwartsluis	IJS	River	-1.0	*-0.8*	5.1	*0.4*	5.2	*0.5*
IJsselmeer (lake)			0.1	*0.0*	1.7	*0.2*	1.7	*0.2*
Markermeer (lake)			-0.4	*-0.3*	0.9	*0.1*	1.0	*0.2*
Veluwerandmeren (lake)			0.7	*0.7*	3.1	*2.1*	3.2	*2.2*
Average			0.2	*-0.3*	3.6	*0.5*	4.1	*0.7*

**Negative Δ values represent a decrease in the statistical metric (more negative or less positive) during Storm Henk compared to the entire period (Dec 11th – Jan 16th).*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate from -3.6 to 0.6 cm and RMSE from 3.7 to 2.6 cm (Δfull = 0.5 cm).*

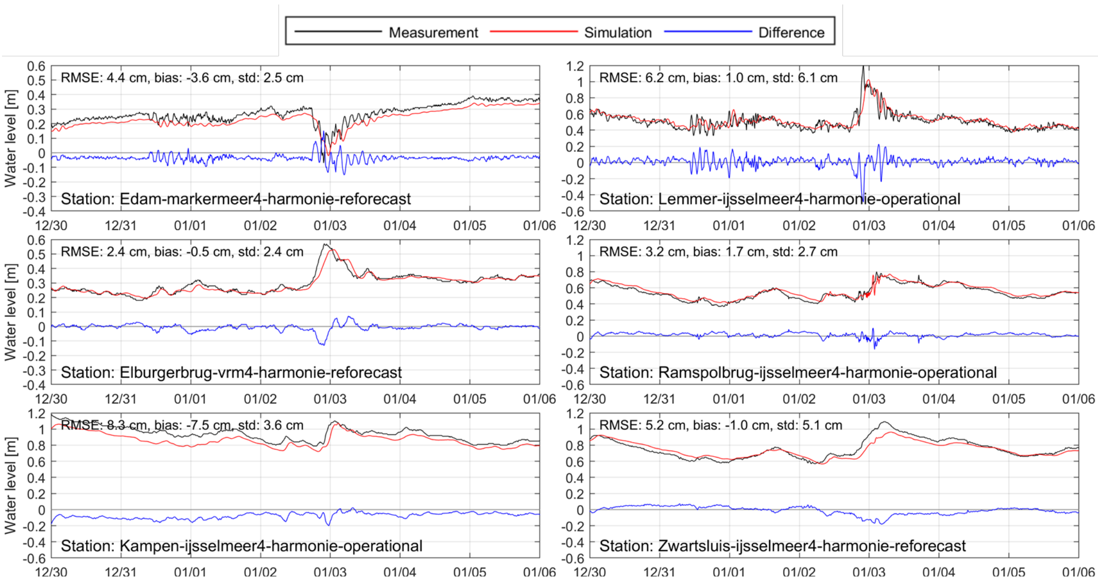

Figure 3.3 – Simulated (red) and observed (black) water levels during Storm Henk, and the difference between the two (blue).

3.2.4 D-HYDRO versus WAQUA model performance

The 6th generation D-HYDRO results were compared to those from 5th generation WAQUA models. Visual comparison of the two water level forecasts shows differences at some stations (e.g. Edam, Kampen, Zwartsluis) and almost identical water levels at other stations (Figure 3.4). At some riverine locations, such as Kampen, the D-HYDRO models perform slightly worse. From a statistical point of view, however, WAQUA models perform very similarly to the D-HYDRO models, with D-HYDRO slightly outperforming WAQUA in terms of STD which is confirmed by the difference in statistical metrics (bias Δ = 0.1 cm, STD Δ = 0.6 cm, RMSE Δ = 0.7 cm). The statistics for a full set of stations can be found in Appendix A.1.

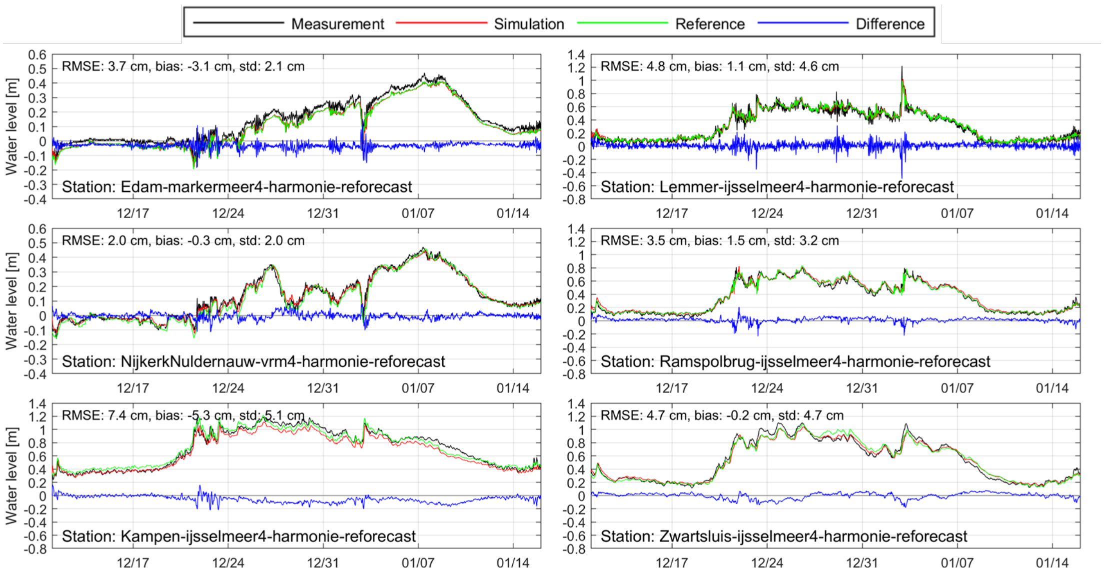

Figure 3.4 - Comparison of simulated water level variation between D-HYDRO (red), WAQUA (green) and measurements (black).

The biggest difference in between D-HYDRO and WAQUA models is at Vechterweerd station, where WAQUA outperforms D-HYDRO (RMSE Δ = -2.7 cm). However, this difference is likely a result of discrepancies in the Vecht boundary conditions introduced by the reforecasting procedure (as explained in Section 2.2). Excluding this station from consideration would however only increase the bias difference between the models from 0.1 to 0.2 cm.

Kampen is another station with relatively large differences between WAQUA and D-HYDRO model results, especially regarding bias (Δ = 3.5 cm). Visual analysis of the extended water level series (October 2023 – February 2024) at this station shows that while D-HYDRO is extremely good at predicting water levels during normal conditions, major bias occurred during Storms Pia and Henk (Figure 3.5, top). At the same time, the WAQUA model is visibly worse at predicting water levels at Kampen, by overestimating them in normal conditions (Figure 3.5, bottom). However, its performance stays at the same level of accuracy during the storms.

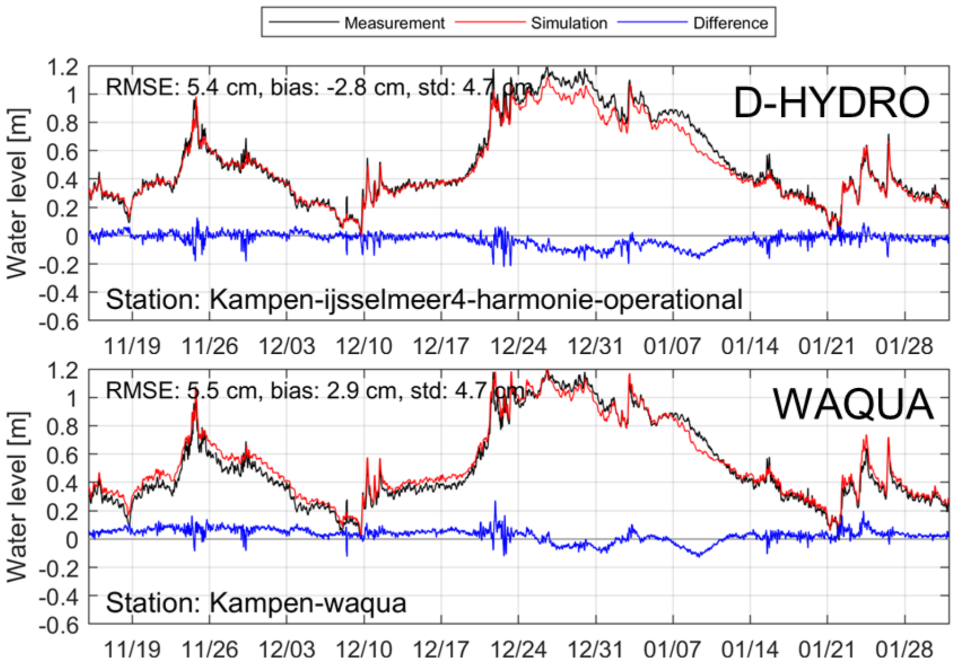

Figure 3.5 – Comparison of water level predictions from D-HYDRO and WAQUA at Kampen station over the extended period between November 2023 and February 2024.

A similar issue could also be affecting the model performance at Katerveer station (Figure 3.6), although the lack of archived operational D-HYDRO and WAQUA data there makes it difficult to determine whether the drop in model performance is a result of the change in some of the lateral discharges in Overijsselse Vecht introduced by the reforecasting procedure.

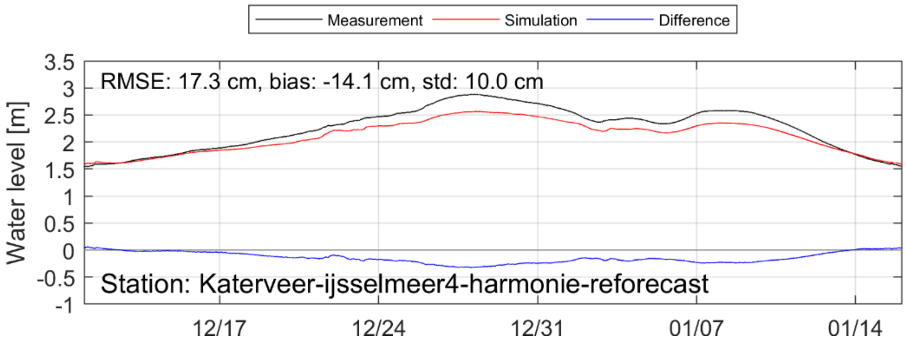

Figure 3.6 – Simulated in D-HYDRO (red) and observed (black) water levels at Zwolle Katerveer station and the difference between the two on reforecasting period between December 12th, 2023, and January 16th, 2024.

3.3 Coarse-gridded model performance

This section compares the performance of the coarse-gridded models with the fine-gridded versions. As described in Section 2.1, the *ijsselmeer4c_harmonie* and *markermeer4c_harmonie* models are considered to have a coarse grid for the purpose of this study.

As may be expected, the coarse models show, in general, a higher margin of error compared to the fine grid models (Figure 3.7). The most prominent deterioration in model quality occurs at riverine stations, where RMSE can reach up to 10 – 30 cm for course-gridded models. Nevertheless, while error increases for almost all stations, the RMSE of the models along the lakeshore and near lake sluices remains within a reasonable range of 3 – 4 cm. Therefore, weighted lake level, a key dataset produced by RWsOS-Meren, is almost unaffected by which model (coarse or fine) is used.

Table 3.5 presents statistical metrics of coarse model performance for the main stations and compares these to the performance observed in fine models (as reported in paragraph 3.2). Statistical metrics for all studied stations can be found in Appendix A.2.

Table 3.5. Performance metrics (in cm) of RWsOS-Meren coarse models at main stations (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias	Δ_{fine}*	STD	Δ_{fine}*	RMSE	Δ_{fine}*
Edam**	MRK	Lake	-3.1	*0.0*	2.1	*0.1*	3.7	*0.0*
Kampen	IJS	River	9.9	*15.2*	5.2	*0.1*	11.1	*3.7*
Lemmer	IJS	Lake	1.3	*0.2*	4.6	*0.0*	4.8	*0.0*
Ramspolbrug	IJS	Lake	3.5	*2.0*	3.1	*-0.1*	4.7	*1.2*
Zwartsluis	IJS	River	4.5	*4.7*	4.7	*0.0*	6.5	*1.8*
IJsselmeer (lake)			0.2	*0.1*	1.6	*0.1*	1.6	*0.1*
Markermeer (lake)			-0.1	*0.0*	0.8	*0.0*	0.8	*0.0*
Average			3.6	*3.4*	4.4	*0.6*	6.4	*1.8*

**Negative Δ values represent decrease in the statistical metric as compared to the fine-gridded D-HYDRO models.*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate from -3.1 to -0.1 cm and RMSE from 3.7 to 2.1 cm (Δfine = 0.0 cm).*

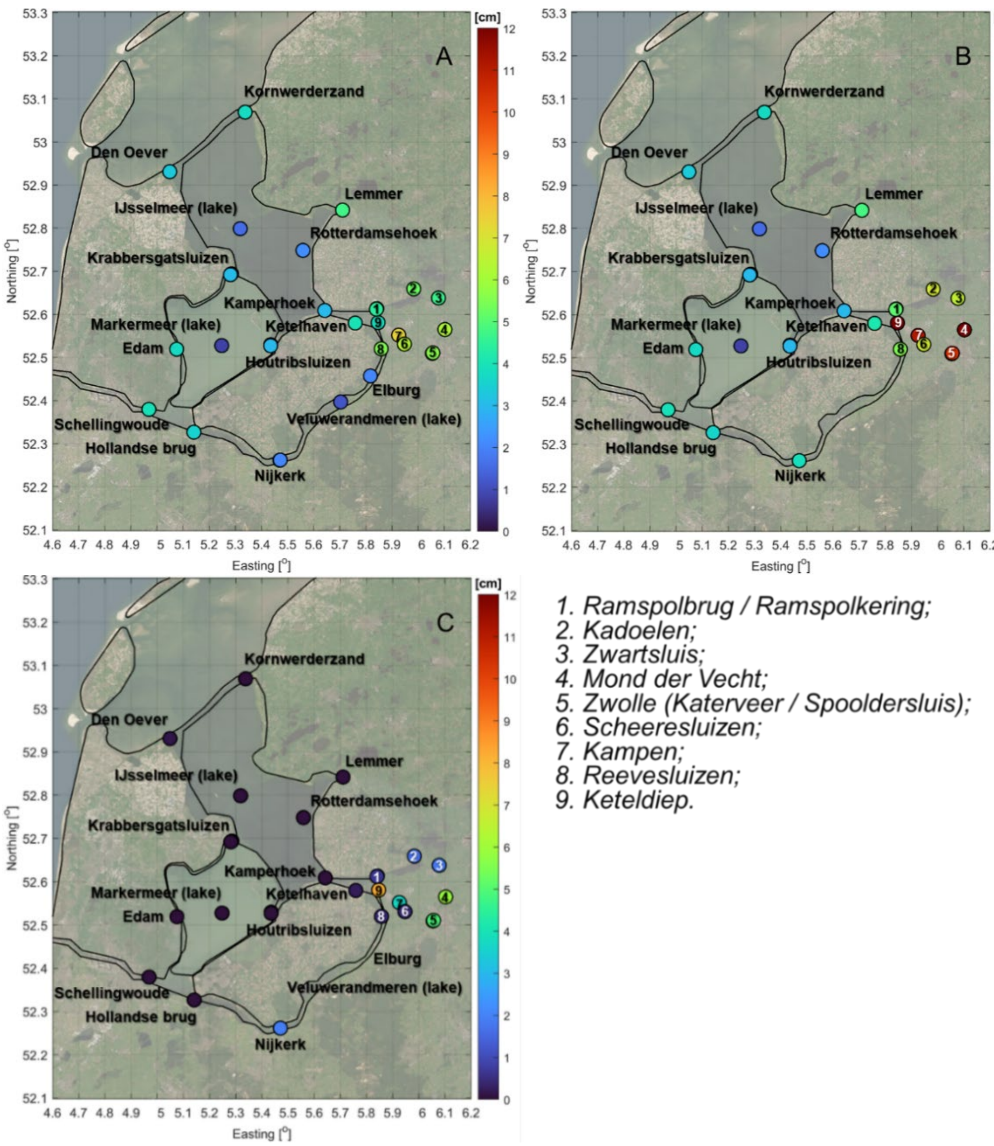

Figure 3.7 – RMSE of water level values simulated by RWsOS-Meren D-HYDRO models on fine (A) and coarse (B) grids and the difference between the two (C).

Coarse-gridded model bias at riverine stations is quite large compared to the bias observed in fine models. Water levels are overestimated at riverine stations by 6 – 25 cm. However, while water levels are also overestimated for almost all the lake stations (except Edam), the magnitude of the bias is only 1 to 3 cm.

Considering the (large) differences in bias and RMSE between the coarse- and fine-gridded models, it is interesting to note that the STD of the modelled water levels does not change much between the two. This signifies that the change in RMSE is driven by the increase in the average water level under- or overestimation (bias) in the coarse models, which is most likely a result of poorer representation of the bathymetry/topography in the coarse grid.

Coarse-gridded model performance was also analysed separately for Storms Pia and Henk. Overall, changes similar to those described for fine-gridded D-HYDRO models in Sections 3.2.2 and 3.2.3 are observed for the water levels during extreme events in the coarse-gridded models. On average, the coarse models overestimated water levels during extreme events by approximately 3 – 4 cm for both storms. While this might suggest that coarse-gridded models could give more sustainable extreme water level estimates, this is not a preferred modelling practice to rely on.

3.4 Weighted lake level

This section discusses the prediction of weighted lake level, which is a parameter derived from sets of stations around each of the lakes. For more detailed explanation of the performance metrics for weighted lake levels with specific models please refer to Section 3.2 and Section 3.3.

Overall, due to the averaging effect of the weighted summation approach, the lake levels derived from the RWsOS-Meren D-HYDRO models match the values derived from measurements quite well, with an RMSE around 1 – 2 cm and near-zero bias for the fine-gridded models. Coarse-gridded models are also able to predict the lake levels sufficiently well (Table 3.5).

Variability (STD) in lake level estimates becomes more prominent during extreme events but is still within relatively small margin compared to the absolute value spread.

Weighted lake levels computed from the WAQUA model results are very similar to the ones obtained from D-HYDRO fine-gridded models (Figure 3.5). The differences in statistical metrics between the two types of models are, on average, less than 1 cm and thus could be considered as negligible.

This high performance is reached by applying lake level correction ("meerpeilcorrectie") in the process of simulating water levels, which optimizes the models to perform best for lake level prediction. Another factor is the averaging effect which is applied during the weighted averaging procedure.

4 Conclusions

The RWsOS-Meren D-HYDRO fine-gridded models perform quite well, with an RMSE of 2 – 4 cm at lake stations and approximately 5 cm at most riverine stations. No consistent under- or overestimation was found during normal circumstances. Weighted lake levels are predicted with an even higher degree of accuracy (1 – 2 cm RMSE) due to the lake level correction (“meerpeilcorrectie”) applied in the modelling procedure and the averaging effect from the weighted calculation approach.

During Storm Pia and Storm Henk, model performance deteriorated slightly, with RMSE increasing by an average of 1 – 3 cm. Moreover, water level peaks occurring during Storm Pia, which could be characterized by dynamic water level growth, were underestimated by the models at most stations, especially along the rivers. This was less pronounced during Storm Henk, which was a stable period of high water. However, a decline in model performance was still visible for Storm Henk, especially for the riverine stations.

RWsOS-Meren D-HYDRO fine-gridded models performed with a similar level of accuracy as the older WAQUA models. While some stations were better represented by the WAQUA models during the storm period, most of the stations were simulated with a higher degree of accuracy by D-HYDRO models. Given the negligible differences in performance between the two sets of models at most of the stations, they can be considered as replicating one another in terms of the resulting analytical information.

However, attention should focus on the deteriorated model performance along the IJssel River, as indicated by the results at Kampen and Zwolle Katerveer, especially during the storms. It is advised to investigate why WAQUA outperforms the D-HYDRO model, in order to further improve the model schematisation.

The reforecasting procedure was found to produce results comparable to archived operational data. The overall RMSE difference between the two did not exceed 0.8 cm, which makes reforecasted data reliable for the sake of evaluating model performance in this study.

Coarse-gridded D-HYDRO models show a slight reduction in accuracy relative to fine-gridded models. However, this reduction is negligible for many stations along the lake shores. The change in resolution mainly affects the performance in riverine areas and is largely caused by the increase in the absolute bias. This suggests that the drop in performance may be caused by poorer representation of the bathymetry in the coarse grid. Coarse models showed similar changes during extreme events to those found for fine-gridded models.

5 Literature

Eijsberg-Bak Carlijn, Asako Fujisaki en Menno Genseberger, D-HYDRO modelschematisatie IJVD - Modelopzet en eerste validatie, Deltares rapport 11206813-009-ZWS-0029, 2022

Eijsberg-Bak Carlijn, Veluwerandmeren WAQUA-model 5de generatie – Modelopzet en validatie, Deltares rapport 1220072-011-ZWS-0006, 2015.

Genseberger Menno, Carlijn Eijsberg-Bak, Remco Plieger, Aukje Spruyt, Asako Fujisaki en Ton Visser, Sneller 2DH D-HYDRO model IJsselmeer en IJVD, Deltares rapport 11208053-006-ZWS-0012, 2022

Genseberger Menno, Sneller 2DH D-HYDRO model Markermeer, Deltares rapport 11208053-007-ZWS-0003, 2022

Genseberger Menno, Uniformering modelinvoer D-HYDRO modelschematisatie Markermeer, Deltares memo 11206813-012-ZWS-0004, 2021.

Genseberger Menno, Asako Fujisaki en Carlijn Eijsberg-Bak, D-HYDRO deelmodel IJsselmeer - modelbouw, eerste modelresultaten waterstanden in 2DH en zoutverspreiding in 3D, Deltares rapport 11205258-008-ZWS-0005, 2020.

Genseberger Menno, Carlijn Eijsberg-Bak, Asako Fujisaki en Christophe Thiange, Ontwikkeling Zesde generatie Markermeer en Veluwerandmeren model – modelbouw en validatie, Deltares rapport 11200569-009-ZWS-0013, 2017.

A Appendix A. Additional tables

A.1 Fine-gridded D-HYDRO model performance metrics – entire period

Appendix Table A.1. RWsOS-Meren fine-gridded D-HYDRO model performance – statistical metrics (December 11, 2023 – January 16, 2024).

Location	Model / Position		Bias, cm	STD, cm	RMSE, cm
Den Oever binnen	IJS	Lake	-0.7	3.2	3.3
Edam*	**MRK**	**Lake**	**-3.1**	**2.1**	**3.7**
Elburgerbrug	**VRM**	**Lake**	**0.2**	**1.8**	**1.8**
Hollandse brug	MRK	Lake	2.5	2.5	3.6
Houtribsluizen noord	IJS	Lake	0.7	3.8	3.9
Houtribsluizen zuid	MRK	Lake	1.6	2.5	3.0
Kadoelen	IJS	River	4.3	3.2	5.4
Kampen	**IJS**	**River**	**-2.8**	**4.7**	**5.4**
Kamperhoek	IJS	Lake	0.0	2.8	2.8
Katerveer	IJS	River	-14	10	17
Keteldiep	IJS	River	1.3	3.3	3.5
Ketelhaven	IJS	R ↔ L	1.6	3.4	3.8
Kornwerderzand binnen	IJS	Lake	-0.6	3.4	3.5
Krabbersgat noord	IJS	Lake	-1.2	2.9	3.1
Krabbersgat zuid	MRK	Lake	-1.1	2.9	3.1
Lemmer	**IJS**	**Lake**	**1.0**	**4.4**	**4.5**
Mond der Vecht	IJS	River	0.8	5.2	5.2
Nijkerk Nijkerkersluis	MRK	Lake	0.9	3.8	3.9
Nijkerk Nuldersluis	VRM	Lake	-0.3	2.0	2.0
Ramspolbrug	**IJS**	**Lake**	**1.8**	**2.7**	**3.2**
Ramspolkering	IJS	Lake	0.8	4.3	4.4
Reevesluis noord	IJS	Lake	1.3	4.8	4.9
Reevesluis zuid	VRM	Lake	1.7	2.4	3.0
Rotterdamsehoek	IJS	Lake	0.0	2.2	2.2
Scheeresluis beneden	IJS	River	1.2	6.2	6.4
Schellingwoude	MRK	Lake	1.7	3.5	3.9
Spooldersluis	IJS	River	-2.0	5.2	5.6
Vechterweerd	IJS	River	14	8.0	16
Zwartsluis	**IJS**	**River**	**-0.2**	**4.7**	**4.7**
IJsselmeer			**0.1**	**1.5**	**1.5**
Markermeer			**-0.1**	**0.8**	**0.8**
Veluwerandmeren			**0.0**	**1.0**	**1.0**
Average			**0.5**	**3.1**	**3.4**
RMS			**1.5**	**3.3**	**3.7**

**After adjustment of Edam measurements by -3 cm, model bias reduces from -3.1 to -0.1 cm and RMSE from 3.7 to 2.1 cm.*

Appendix Table A.2. RWsOS-Meren fine-gridded D-HYDRO model performance during Storm Pia (December 19th through 25th, 2023) – statistical metrics (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			Pia	Δ_{full}*	full	Pia	Δ_{full}*	full	Pia	Δ_{full}*	full
Den Oever binnen	IJS	Lake	-1.2	*-0.5*	-0.7	4.4	*1.2*	3.2	4.6	*1.3*	3.3
Edam**	**MRK**	**Lake**	**-3.2**	***-0.1***	**-3.1**	**2.9**	***0.8***	**2.1**	**4.3**	***0.6***	**3.7**
Elburgerbrug	**VRM**	**Lake**	**-0.5**	***-0.7***	**0.2**	**2.0**	***0.2***	**1.8**	**2.1**	***0.3***	**1.8**
Hollandse brug	MRK	Lake	3.4	*0.9*	2.5	3.0	*0.5*	2.5	4.5	*0.9*	3.6
Houtribsluizen noord	IJS	Lake	1.2	*0.5*	0.7	5.5	*1.7*	3.8	5.6	*1.7*	3.9
Houtribsluizen zuid	MRK	Lake	0.8	*-0.8*	1.6	3.7	*1.2*	2.5	3.8	*0.8*	3.0
Kadoelen	IJS	River	1.2	*-3.1*	4.3	4.1	*0.9*	3.2	4.2	*-1.2*	5.4
Kampen	**IJS**	**River**	**-4.4**	***-1.6***	**-2.8**	**4.5**	***-0.2***	**4.7**	**6.3**	***0.9***	**5.4**
Kamperhoek	IJS	Lake	-0.4	*-0.4*	0.0	4.3	*1.5*	2.8	4.4	*1.6*	2.8
Katerveer	IJS	River	-16	*-1.8*	-14	3.5	*-6.5*	10	16	*-1.0*	17
Keteldiep	IJS	River	-0.1	*-1.4*	1.3	5.1	*1.8*	3.3	5.1	*1.6*	3.5
Ketelhaven	IJS	R ⇔ L	0.7	*-0.9*	1.6	5.3	*1.9*	3.4	5.3	*1.5*	3.8
Kornwerderzand binnen	IJS	Lake	-2.0	*-1.4*	-0.6	4.6	*1.2*	3.4	5.0	*1.5*	3.5
Krabbersgat noord	IJS	Lake	-1.3	*-0.1*	-1.2	3.3	*0.4*	2.9	3.6	*0.5*	3.1
Krabbersgat zuid	MRK	Lake	-2.9	*-1.8*	-1.1	3.1	*0.2*	2.9	4.3	*1.2*	3.1
Lemmer	**IJS**	**Lake**	**0.1**	***-0.9***	**1.0**	**5.3**	***0.9***	**4.4**	**5.3**	***0.8***	**4.5**
Mond der Vecht	IJS	River	-3.4	*-4.2*	0.8	3.7	*-1.5*	5.2	5.0	*-0.2*	5.2
Nijkerk Nijkerkersluis	MRK	Lake	0.8	*-0.1*	0.9	4.8	*1.0*	3.8	4.9	*1.0*	3.9
Nijkerk Nuldersluis	VRM	Lake	-1.0	*-0.7*	-0.3	2.3	*0.3*	2.0	2.5	*0.5*	2.0
Ramspolbrug	**IJS**	**Lake**	**0.1**	***-1.7***	**1.8**	**3.6**	***0.9***	**2.7**	**3.6**	***0.4***	**3.2**
Ramspolkering Ketelmeerzijde	IJS	Lake	-0.9	*-1.7*	0.8	6.5	*2.2*	4.3	6.5	*2.1*	4.4
Reevesluis noord	IJS	Lake	0.4	*-0.9*	1.3	6.5	*1.7*	4.8	6.5	*1.6*	4.9
Reevesluis zuid	VRM	Lake	1.3	*-0.4*	1.7	2.7	*0.3*	2.4	3.0	*0.0*	3.0
Rotterdamsehoek	IJS	Lake	-0.4	*-0.4*	0.0	3.0	*0.8*	2.2	3.1	*0.9*	2.2
Scheeresluis beneden	IJS	River	0.2	*-1.0*	1.2	9.5	*3.3*	6.2	9.5	*3.1*	6.4
Schellingwoude	MRK	Lake	3.0	*1.3*	1.7	4.5	*1.0*	3.5	5.4	*1.5*	3.9

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			Pia	Δ_{full}*	full	Pia	Δ_{full}*	full	Pia	Δ_{full}*	full
Spooldersluis	IJS	River	-3.7	*-1.7*	-2.0	7.3	*2.1*	5.2	8.2	*2.6*	5.6
Vechterweerd	IJS	River	8.8	*-5.6*	14	3.7	*-4.3*	8.0	9.5	*-7.0*	16
Zwartsluis	**IJS**	**River**	**-5.4**	***-5.2***	**-0.2**	**4.3**	***-0.4***	**4.7**	**6.8**	***2.1***	**4.7**
IJsselmeer			**-0.4**	***-0.5***	**0.1**	**1.9**	***0.4***	**1.5**	**1.9**	***0.4***	**1.5**
Markermeer			**-0.4**	***-0.3***	**-0.1**	**0.7**	***-0.1***	**0.8**	**0.8**	***0.0***	**0.8**
Veluwerandmeren			**-0.7**	***-0.7***	**0.0**	**0.7**	***-0.3***	**1.0**	**1.0**	***0.0***	**1.0**
Average			**-0.6**	***-1.1***	**0.5**	**3.9**	***0.8***	**3.1**	**4.2**	***0.8***	**3.4**
RMS			**1.6**	***0.1***	**1.5**	**4.1**	***0.8***	**3.3**	**4.4**	***0.7***	**3.7**

**Negative Δ values represent a decrease in the statistical metric during Storm Pia compared to the entire period (Dec 11th – Jan 16th).*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate for Storm Pia from -3.2 to -0.2 cm and RMSE from 4.3 to 2.9 cm (Δ = 0.8 cm).*

Appendix Table A.3. RWsOS-Meren fine-gridded D-HYDRO model performance during Storm Henk (December 31st, 2023, through January 6th, 2024) – statistical metrics (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			Henk	Δ_{full}*	full	Henk	Δ_{full}*	full	Henk	Δ_{full}*	full
Den Oever binnen	IJS	Lake	-0.8	*-0.1*	-0.7	3.3	*0.1*	3.2	3.4	*0.1*	3.3
Edam**	**MRK**	**Lake**	**-3.6**	***-0.5***	**-3.1**	**2.5**	***0.4***	**2.1**	**4.4**	***0.7***	**3.7**
Elburgerbrug	**VRM**	**Lake**	**-0.5**	***-0.7***	**0.2**	**2.2**	***0.4***	**1.8**	**2.3**	***0.5***	**1.8**
Hollandse brug	MRK	Lake	2.5	*0.0*	2.5	3.5	*1.0*	2.5	4.3	*0.7*	3.6
Houtribsluizen noord	IJS	Lake	0.9	*0.2*	0.7	3.6	*-0.2*	3.8	3.7	*-0.2*	3.9
Houtribsluizen zuid	MRK	Lake	1.3	*-0.3*	1.6	2.6	*0.1*	2.5	3.0	*0.0*	3.0
Kadoelen	IJS	River	3.8	*-0.5*	4.3	3.4	*0.2*	3.2	5.1	*-0.3*	5.4
Kampen	**IJS**	**River**	**-7.5**	***-4.7***	**-2.8**	**3.6**	***-1.1***	**4.7**	**8.3**	***2.9***	**5.4**
Kamperhoek	IJS	Lake	0.0	*0.0*	0.0	2.3	*-0.5*	2.8	2.3	*-0.5*	2.8
Katerveer	IJS	River	-19	*-5.3*	-14	3.4	*-6.6*	10	20	*2.4*	17
Keteldiep	IJS	River	1.3	*0.0*	1.3	2.9	*-0.4*	3.3	3.2	*-0.3*	3.5
Ketelhaven	IJS	R ⇔ L	1.7	*0.1*	1.6	3.0	*-0.4*	3.4	3.5	*-0.3*	3.8
Kornwerderzand binnen	IJS	Lake	-0.7	*-0.1*	-0.6	3.7	*0.3*	3.4	3.8	*0.3*	3.5

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			Henk	Δ_{full}*	full	Henk	Δ_{full}*	full	Henk	Δ_{full}*	full
Krabbersgat noord	IJS	Lake	-1.2	*0.0*	-1.2	3.3	*0.4*	2.9	3.5	*0.4*	3.1
Krabbersgat zuid	MRK	Lake	-1.6	*-0.5*	-1.1	3.4	*0.5*	2.9	3.7	*0.6*	3.1
Lemmer	**IJS**	**Lake**	**1.0**	***0.0***	**1.0**	**6.1**	***1.7***	**4.4**	**6.2**	***1.7***	**4.5**
Mond der Vecht	IJS	River	-0.6	*-1.4*	0.8	5.8	*0.6*	5.2	5.8	*0.6*	5.2
Nijkerk Nijkerkersluis	MRK	Lake	1.0	*0.1*	0.9	4.8	*1.0*	3.8	4.9	*1.0*	3.9
Nijkerk Nuldersluis	VRM	Lake	1.6	*1.9*	-0.3	5.7	*3.7*	2.0	5.9	*3.9*	2.0
Ramspolbrug	**IJS**	**Lake**	**1.7**	***-0.1***	**1.8**	**2.7**	***0.0***	**2.7**	**3.2**	***0.0***	**3.2**
Ramspolkering	IJS	Lake	1.5	*0.7*	0.8	4.4	*0.1*	4.3	4.6	*0.2*	4.4
Reevesluis noord	IJS	Lake	1.3	*0.0*	1.3	4.9	*0.1*	4.8	5.1	*0.2*	4.9
Reevesluis zuid	VRM	Lake	1.2	*-0.5*	1.7	3.1	*0.7*	2.4	3.3	*0.3*	3.0
Rotterdamsehoek	IJS	Lake	0.1	*0.1*	0.0	2.1	*-0.1*	2.2	2.1	*-0.1*	2.2
Scheeresluis beneden	IJS	River	0.9	*-0.3*	1.2	6.4	*0.2*	6.2	6.4	*0.0*	6.4
Schellingwoude	MRK	Lake	1.6	*-0.1*	1.7	4.5	*1.0*	3.5	4.8	*0.9*	3.9
Spooldersluis	IJS	River	-3.0	*-1.0*	-2.0	5.4	*0.2*	5.2	6.1	*0.5*	5.6
Vechterweerd	IJS	River	16	*1.5*	14	9.0	*1.0*	8.0	18	*1.8*	16
Zwartsluis	**IJS**	**River**	**-1.0**	***-0.8***	**-0.2**	**5.1**	***0.4***	**4.7**	**5.2**	***0.5***	**4.7**
IJsselmeer			**0.1**	***0.0***	**0.1**	**1.7**	***0.2***	**1.5**	**1.7**	***0.2***	**1.5**
Markermeer			**-0.4**	***-0.3***	**-0.1**	**0.9**	***0.1***	**0.8**	**1.0**	***0.2***	**0.8**
Veluwerandmeren			**0.7**	***0.7***	**0.0**	**3.1**	***2.1***	**1.0**	**3.2**	***2.2***	**1.0**
Average			**0.2**	***-0.3***	**0.5**	**3.6**	***0.5***	**3.1**	**4.1**	***0.7***	**3.4**
RMS			**2.2**	***0.7***	**1.5**	**3.8**	***0.5***	**3.3**	**4.4**	***0.7***	**3.7**

**Negative Δ values represent a decrease in the statistical metric during Storm Henk compared to the entire period (Dec 11th – Jan 16th).*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate for Storm Henk from -3.6 to -0.6 cm and RMSE from 4.4 to 2.6 cm (Δ = 0.6 cm).*

A.2 Coarse-gridded D-HYDRO model performance metrics

Appendix Table A.4. RWsOS-Meren coarse-gridded D-HYDRO model performance – statistical metrics (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			coarse	Δ_{full}*	fine	coarse	Δ_{full}*	fine	coarse	Δ_{full}*	fine
Den Oever binnen	IJS	Lake	-0.7	*0.0*	-0.7	3.3	*0.1*	3.2	3.4	*0.1*	3.3
Edam**	**MRK**	**Lake**	-3.1	*0.0*	**-3.1**	2.1	*0.0*	**2.1**	3.7	*0.0*	**3.7**
Hollandse brug	MRK	Lake	2.6	*0.1*	2.5	2.5	*0.0*	2.5	3.6	*0.0*	3.6
Houtribsluizen noord	IJS	Lake	1.0	*0.3*	0.7	4.0	*0.2*	3.8	4.1	*0.2*	3.9
Houtribsluizen zuid	MRK	Lake	1.7	*0.1*	1.6	2.5	*0.0*	2.5	3.0	*0.0*	3.0
Kadoelen	IJS	River	6.0	*1.7*	4.3	3.4	*0.2*	3.2	6.9	*1.5*	5.4
Kampen	**IJS**	**River**	9.9	*13*	**-2.8**	5.2	*0.5*	**4.7**	11	*5.7*	**5.4**
Kamperhoek	IJS	Lake	0.1	*0.1*	0.0	3.0	*0.2*	2.8	3.0	*0.2*	2.8
Katerveer	IJS	River	11	*25*	-14	12	*2.0*	10	16	*-1.3*	17
Keteldiep	IJS	River	11	*10*	1.3	4.0	*0.7*	3.3	12	*8.5*	3.5
Ketelhaven	IJS	R ↔ L	2.0	*0.4*	1.6	3.7	*0.3*	3.4	4.2	*0.4*	3.8
Kornwerderzand binnen	IJS	Lake	-0.6	*0.0*	-0.6	3.7	*0.3*	3.4	3.7	*0.2*	3.5
Krabbersgat noord	IJS	Lake	-1.1	*0.1*	-1.2	2.9	*0.0*	2.9	3.1	*0.0*	3.1
Krabbersgat zuid	MRK	Lake	-1.1	*0.0*	-1.1	2.8	*-0.1*	2.9	3.0	*-0.1*	3.1
Lemmer	**IJS**	**Lake**	1.3	*0.3*	**1.0**	4.6	*0.2*	**4.4**	4.8	*0.3*	**4.5**
Mond der Vecht	IJS	River	9.1	*8.3*	0.8	8.0	*2.8*	5.2	12	*6.9*	5.2
Nijkerk Nijkerkersluis	MRK	Lake	0.9	*0.0*	0.9	3.8	*0.0*	3.8	3.9	*0.0*	3.9
Ramspolbrug	**IJS**	**Lake**	3.5	*1.7*	**1.8**	3.1	*0.4*	**2.7**	4.7	*1.5*	**3.2**
Ramspolkering	IJS	Lake	2.2	*1.4*	0.8	4.6	*0.3*	4.3	5.1	*0.7*	4.4
Reevesluis noord	IJS	Lake	1.9	*0.6*	1.3	5.2	*0.4*	4.8	5.5	*0.6*	4.9
Rotterdamsehoek	IJS	Lake	0.1	*0.1*	0.0	2.2	*0.0*	2.2	2.2	*0.0*	2.2
Scheeresluis beneden	IJS	River	2.0	*0.8*	1.2	6.5	*0.3*	6.2	6.8	*0.4*	6.4
Schellingwoude	MRK	Lake	1.7	*0.0*	1.7	3.5	*0.0*	3.5	3.9	*0.0*	3.9
Spooldersluis	IJS	River	8.2	*10*	-2.0	6.5	*1.3*	5.2	10	*4.9*	5.6
Vechterweerd	IJS	River	26	*12*	14	13	*5.0*	8.0	29	*13*	16

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			coarse	*Δ_{full}**	fine	coarse	*Δ_{full}**	fine	coarse	*Δ_{full}**	fine
Zwartsluis	**IJS**	**River**	4.5	*4.7*	**-0.2**	4.7	*0.0*	**4.7**	6.5	*1.8*	**4.7**
IJsselmeer			0.2	*0.1*	**0.1**	1.6	*0.1*	**1.5**	1.6	*0.1*	**1.5**
Markermeer			-0.1	*0.0*	**-0.1**	0.8	*0.0*	**0.8**	0.8	*0.0*	**0.8**
Veluwerandmeren			3.6	*3.1*	**0.0**	4.4	*1.3*	**1.0**	6.4	*3.0*	**1.0**
Average			6.8	*5.3*	**0.5**	5.2	*1.9*	**3.1**	8.5	*4.8*	**3.4**
RMS			0.2	*0.1*	**1.5**	1.6	*0.1*	**3.3**	1.6	*0.1*	**3.7**

**Negative Δ values represent decrease in the statistical metric as compared to the fine-gridded D-HYDRO models.*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate for coarse models from -3.1 to -0.1 cm and RMSE from 3.7 to 2.1 cm (Δ = 0.0 cm).*

A.3 WAQUA model performance metrics

Appendix Table A.5. RWsOS-Meren WAQUA model performance – statistical metrics (December 11, 2023 – January 16, 2024).

Location	Model	Position	Bias, cm			STD, cm			RMSE, cm		
			WAQ	Δ_{full}*	DHYD	WAQ	Δ_{full}*	DHYD	WAQ	Δ_{full}*	DHYD
Den Oever binnen	IJS	Lake	-1.1	*-0.4*	-0.7	3.0	*-0.2*	3.2	3.2	*-0.1*	3.3
Edam**	**MRK**	**Lake**	**-3.2**	***-0.1***	**-3.1**	**2.0**	***-0.1***	**2.1**	**3.8**	***0.1***	**3.7**
Hollandse brug	MRK	Lake	2.6	*0.1*	2.5	2.2	*-0.3*	2.5	3.4	*-0.2*	3.6
Houtribsluizen noord	IJS	Lake	0.9	*0.2*	0.7	3.6	*-0.2*	3.8	3.7	*-0.2*	3.9
Houtribsluizen zuid	MRK	Lake	1.8	*0.2*	1.6	2.5	*0.0*	2.5	3.0	*0.0*	3.0
Kadoelen	IJS	River	2.5	*-1.8*	4.3	3.1	*-0.1*	3.2	4.0	*-1.4*	5.4
Kampen	**IJS**	**River**	**0.7**	***3.5***	**-2.8**	**5.2**	***0.5***	**4.7**	**5.2**	***-0.2***	**5.4**
Kamperhoek	IJS	Lake	0.1	*0.1*	0.0	2.6	*-0.2*	2.8	2.6	*-0.2*	2.8
Keteldiep	IJS	River	1.9	*0.6*	1.3	3.2	*-0.1*	3.3	3.7	*0.2*	3.5
Ketelhaven	IJS	R ↔ L	1.4	*-0.2*	1.6	3.1	*-0.3*	3.4	3.4	*-0.4*	3.8
Kornwerderzand binnen	IJS	Lake	-1.4	*-0.8*	-0.6	3.3	*-0.1*	3.4	3.6	*0.1*	3.5
Krabbersgat noord	IJS	Lake	-1.1	*0.1*	-1.2	2.7	*-0.2*	2.9	3.0	*-0.1*	3.1
Krabbersgat zuid	MRK	Lake	-1.0	*0.1*	-1.1	2.8	*-0.1*	2.9	3.0	*-0.1*	3.1
Lemmer	**IJS**	**Lake**	**1.2**	***0.2***	**1.0**	**3.9**	***-0.5***	**4.4**	**4.1**	***-0.4***	**4.5**
Mond der Vecht	IJS	River	2.2	*1.4*	0.8	7.1	*1.9*	5.2	7.4	*2.2*	5.2
Nijkerk Nijkerkersluis	MRK	Lake	1.4	*0.5*	0.9	3.4	*-0.4*	3.8	3.7	*-0.2*	3.9
Nijkerk Nuldersluis	VRM	Lake	-1.4	*-1.1*	-0.3	2.4	*0.4*	2.0	2.8	*0.8*	2.0
Ramspolbrug	**IJS**	**Lake**	**0.8**	***-1.0***	**1.8**	**3.1**	***0.4***	**2.7**	**3.2**	***0.0***	**3.2**
Schellingwoude	MRK	Lake	1.5	*-0.2*	1.7	2.9	*-0.6*	3.5	3.3	*-0.6*	3.9
Spooldersluis	IJS	River	0.0	*2.0*	-2.0	6.1	*0.9*	5.2	6.1	*0.5*	5.6
Vechterweerd	IJS	River	3.4	*-11*	14	13	*5.4*	8.0	14	*-2.7*	16
Zwartsluis	**IJS**	**River**	**0.0**	***0.2***	**-0.2**	**5.3**	***0.6***	**4.7**	**5.3**	***0.6***	**4.7**
IJsselmeer			**-0.2**	***-0.3***	**0.1**	**1.4**	***-0.1***	**1.5**	**1.5**	***0.0***	**1.5**
Markermeer			**-0.1**	***0.0***	**-0.1**	**1.1**	***0.3***	**0.8**	**1.1**	***0.3***	**0.8**
Average			**0.6**	***0.1***	**0.5**	**3.7**	***0.6***	**3.1**	**4.1**	***0.7***	**3.4**
RMS			**1.6**	***0.1***	**1.5**	**4.4**	***1.1***	**3.3**	**4.7**	***1.0***	**3.7**

**Negative Δ values represent decrease in the statistical metric of WAQUA models as compared to the fine-gridded D-HYDRO models.*

***Measurement data in Edam were recently calibrated and adjusted by approximately 3 cm downwards, reducing the model bias estimate for WAQUA models from -3.2 to -0.2 cm and RMSE from 3.8 to 2.0 cm (Δ = -0.1 cm).*

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