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Assessment of model improvement actions in river hydrodynamic modelling

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ABSTRACT: The usefulness of hydrodynamic river models much depends on the accuracy of the model. The uncertainty in the results of hydrodynamic river models typically originates from uncertainties in the model parameters (calibration uncertainty), model schematization and input data. Based on a detailed insight in the river system, the modelling process and its shortcomings, most efficient model improvement actions can be designed.

In this paper, several model improvement actions are suggested and tested for the hydrodynamic model of the Demer river in Belgium. A detailed model performance evaluation is conducted for that case based on field measurements of river water levels and discharges at different places along the river. The evaluation includes comparison of observed and simulated rainfall-runoff and river peak flows, low flows, cumulative volumes and empirical extreme value distributions.

1 INTRODUCTION

River models have become powerful tools in a wide variety of water related studies. Full hydrodynamic river models make it possible to evaluate the effect of various types of scenarios such as new structures on the rivers, or to calculate the effect of climate change or to predict floods and droughts. In order to produce relevant results, it is important that the river model accurately describes the real river system. By gaining more knowledge on the river system and modelling techniques, actions can be taken to improve the accuracy and performance of river models and to decrease the uncertainty in the model output. There is no need to explain the importance to focus research on those model improvement actions which have the strongest impact.

River models may be uncertain due to many reasons, which commonly can be related to model input, model parameters and model structure. One of the major factors that contribute to the total uncertainty, certainly for well-calibrated models, is the rainfall input uncertainty (Butts et al., 2004). To evaluate the uncertainty and the effect of model improvement actions, many methods have been developed over the years (Duan et al., 1992; Beven and Freer, 2001; Muleta and Nicklow, 2005; Tolson and Shoemaker, 2007). The different methods focus on different aspects and it is hard to compare results of the different methodologies. Arheimer et al. (2011) have recently proposed a method that harmonises the quantitative comparison between different studies. They propose to calculate the obtained improvement (i.e. the fraction of the original error that was removed by a particular modification) as a basis to compare different improvement actions. The advantage of this method is that it enables easy comparison between the effects of different improvement actions. The disadvantage is that it does not allow to provide a detailed investigation on uncertainty propagation in the river model. Since the goal in this paper is to provide a global assessment on improvement actions in river modelling the method of Arheimer et al. (2011) is followed and applied to the Demer river in Belgium.

In addition to the quantitative comparison, also a qualitative comparison is demonstrated. This quanitative comparison focuses on the peak and low flows, by comparing the extreme value ditributions. Also the cumulative flow volumes are tested. The case study is presented in section 2. The different considered improvement actions are described in section 3 and the results summarized in section 4.

2 CASE STUDY

2.1 *Demer river and basin*

The Demer river is located in the eastern part of the Flanders region in Belgium (Figure 1). The Demer basin has an area of 2276 km^2 and the total length of the river is 85 km. The Demer basin is characterized by a densely populated area and has regularly been struck by floods in the last decades (January 1995, September 1998, December 2002 and January 2011). The cities along the Demer (Diest, Zichem, Aarschot) are protected against flooding by two retention reservoirs with a total storage capacity of 8 million m^3. The land use distribution in the basin is shown in Figure 2. The main sub-catchments in the Demer basin are listed in Table 1.

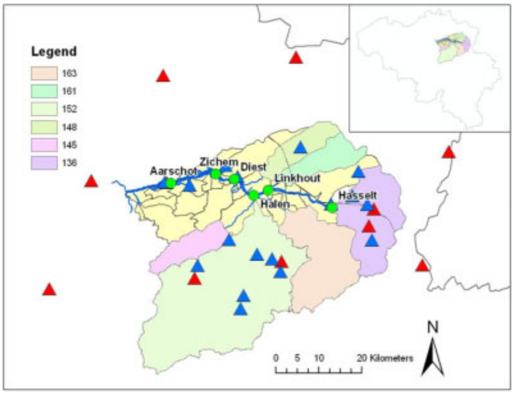

Figure 1. Map of Demer basin showing the main subcatchments, pluviographs (triangle: HIC (red), RMI (blue)) and gauging stations (green circle).

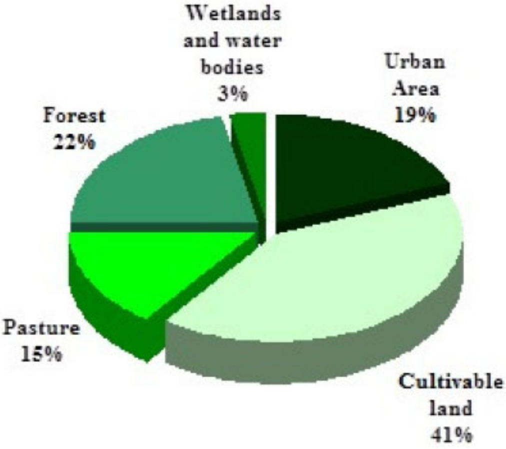

Figure 2. Land use distribution in the Demer basin.

Table 1. Catchment area of the main subcatchments of the Demer basin.

Station ID and Sub-catchments	Catchment Area [km^2]	Relative catchment area in Demer basin [%]
Station 136: Demer Hasselt	366.90	16.12
Station 145: Velp Ransberg	92.90	4.08
Station 148: Zwartebeek Lummen	96.30	4.23
Station 152: Gete Halen	810.50	35.61
Station 161: Mangelbeek Lummen	100.66	4.42
Station 163: Herk Kermt	278.17	12.22

2.2 *Models*

In this study two different software packages in river modelling are used. The first package is the Mike 11 software from DHI Water & Environment (DHI, 2007a; DHI, 2007b) and consists of catchment hydrological and river hydrodynamic models. The hydrological models are implemented in the NAM module. NAM is a lumped conceptual rainfall runoff model (Nielsen and Hansen, 1973; Madsen, 2000). The Mike 11 hydrodynamic model is a one dimensional model, but a quasi-2D approach can be obtained by schematizing the floodplain as a network of fictitious 1D branches and spills (Willems et al., 2002).

The second software package is the InfoWorks modelling system of Innovyze. The hydrological models in this system are represented by probability distributed models (PDM) (Moore, 1985; Moore, 2007). Like NAM, PDM is a lumped conceptual rainfall-runoff model. The InfoWorks-RS hydrodynamic model is also a 1D model, solving the full hydrodynamic model equations (i.e. de St. Venant equations).

The main difference between the two models is that the Infoworks-RS model only contains the upstream part of the Demer (upstream the gauging station at Diest). The Mike11 model contains the complete Demer river.

In both hydrodynamic models all the hydraulic relevant structures are implemented. Cross section data are implemented approximately every 50m along the river reaches.

3 IMPROVEMENT ACTIONS

The improvement actions considered in this study can basically be divided in three categories: input, model schematization and model refinement.

In the input category, the use of additional rainfall input data is studied, by making use of rainfall gauging stations of two different sources: Hydrological Information Centre (HIC) of the Flemish Government and Royal Meteorological Institute of Belgium (RMI). The location of the different raingauges is shown in Figure 1. The HIC rainfall data is hourly data collected by recording raingauges. The RMI data are from non-recording rain gauges, with a daily frequency. The original HIC data were validated, by deleting all the unrealistic high and negative values and for practical reasons, the incomplete series were filled up , by the data of the closest rain gauge, to obtain complete datasets. Because the recording raingauges are of the tipping bucket type, the data contains systematic and random errors, due to mechanical limitations, wind effects and evaporation losses (Moleni et al., 2001; la Barbera et al., 2002; Shedekar et al., 2009; McMillan et al., 2011). The systematic error of each HIC rain gauges incomparison with the nearest RMI gauges has been eliminated by making use of a correction factor. The correction factor was calculated by minimizing the root mean square error of the difference in cumulative raingfall volume. In order to obtain hourly RMI data, an hourly variation is given to the daily RMI data based on the rainfall intensity of the nearest rain gauge. Hence two rainfall input scenarios are considered in this study. The first scenario makes only use of

Table 2. Monthly historical averaged ET (period 1967–2000).

Month	Jan	Feb	Mar	Apr	May	Jun
ET [mm/month]	9.1	10	15.7	34.9	64.2	101.8
Month	Jul	Aug	Sep	Oct	Nov	Dec
ET [mm/month]	106.9	110.4	94.3	64.9	33.0	11.3

Table 3. Old and new dimensions of the Grote Steunbeer as implemented in Mike11 hydrodynamic model.

		old	new
Control structure	Gate width [m]	4.00	4.47
	Sill level [mTAW]	17.30	17.68
	Gate level [mTAW]	18.10	18.63
Weir 1	Datum [mTAW]	20.40	20.30
	Width [m]	4.00	3.92
Weir 2	Datum [mTAW]	20.40	20.27
	Width [m]	4.00	3.95
Weir 3	Datum [mTAW]	20.40	20.85
	Width [m]	4.00	4.47

the HIC rain gauges, whereas in the second scenario, both the HIC and RMI data are used.

Next to the use of more rainfall input data also the use of more detailed evapotranspiration (ET) input data is studied. The RMI calculates the ET at Uccle (Belgium) on a daily basis using the method of Bultot et al. (1983). To test the influence of the accuracy of the ET input data, a monthly historical averaged ET series is calculated. This series contains the average monthly ET calculated for the period (1967-2006). The values of each month can be found in Table 2. Two ET input scenarios were considered, the first making use of the daily calculated ET series and the second making use of the monthly averaged ET series.

In the second category of improvement actions, other model schematizations are considered. Therefore two different river modelling software packages are used, as already stated in section 2.2. In general the two modelling packages are very similar. Both hydrological models (NAM and PDM) are lumped conceptual models and the hydrodynamic models (Mike 11 and Infoworks-RS) are 1D models, solving the full de St. Venant equations. Despite these similarities some differences exist in the model schematization. In PDM the soil water storage is not modelled by one single reservoir, but by a collection of storage reservoirs and the used PDM only generates two runoff subflows (quick flow and slow flow), whereas in NAM also an interflow component is generated. Also in the hydrodynamic model differences exist, e.g. in the submodel for bridges. In Infoworks-RS bridges are modelled based on empirical relations. These relations are derived from laboratory and field experiments. In Mike11 bridges are modelled as culverts with theoretical standard head loss coefficients (Willems et al., 2000).

In the third category of improvement actions, i.e. model refinement, the influence of more detailed modelling is tested. This is done by adjusting the dimensions of a control structure called 'Grote Steunbeer' on the Demer river, which strongly controls the river flow upstream the city of Diest. This structure was built in 1987 and consists of three gates. Two of the gates are of the overflow type, the third weir allows under- and overflow. The implementation of this structure in the Mike11 model was based on estimations of the dimensions and by calibration. However, recently a detailed topographical survey has provided the real dimensions of this structure. The influence of these 'new' dimensions is studied in comparison with the 'old' estimated dimensions. The structure was implemented in Mike11 as three weirs, to simulate the overflow, and as one control structure, simulating the underflow of the third gate. The 'old' and 'new' dimensions are listed in Table 3.

Table 4. Studied improvement actions incorporated in different simulation scenarios.

Scenario	Rainfall input	ET input	Hydrological model	Hydrodynamic Model
1	HIC	Monthly	NAM	Mike11
2	HIC +RMI	Monthly	NAM	Mike11
3	HIC	Monthly	PDM	InfoWorks-RS
4	HIC +RMI	Monthly	PDM	InfoWorks-RS
5	HIC	Daily	NAM	Mike11
6	HIC +RMI	Daily	NAM	Mike11
7	HIC +RMI	Daily	NAM	Mike11 + 'new' dimensions Grote Steunbeer

The different model improvement actions are incorporated in seven different scenarios, which are listed in Table 4.

4 RESULTS

4.1 *Qualitative comparison*

First a qualitative comparison between the different scenarios has been executed. This evaluation includes the comparison of the cumulative volumes, river peak flow and low flows by means of the empirical extreme value distributions. This evaluation method can also be found in Van Steenbergen & Willems (2011). The qualitative comparison is executed for the results of the river flows in the Demer at Hasselt. The method involves separation of the time series in nearly independent quick flow and slow flow hydrograph events.

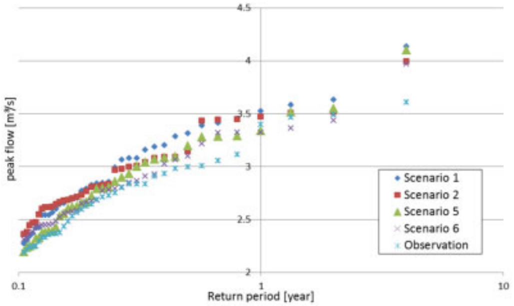

Figure 3. Empirical extreme value distribution of peak flows transformation for scenarios 1,2,5 and 6. Demer at Hasselt.

These events are selected based on the time series processing tool of Willems (2009).

Two subsequent peak events are classified as nearly independent when the following three criteria are fulfilled:

- The time length of the decreasing flank of the first event exceeds a minimum time. This time can be taken equal to the recession constant of the quick flow, or higher.
- The discharge drops down -in between two events- to a fraction lower than a given threshold fraction value of the peak flow.
- The discharge increment of the peak flow above the lowest flow (between the two events) must have a minimum height. This criterion is needed to avoid that small noise peaks are selected. The minimum peak height is consequently taken equal to the highest noise peak.

A similar procedure is used to select the low flows and slow flow hydrograph periods. Instead of using the recession constant of the quick flow, the recession constant of the baseflow (or higher) is used as minimum time length.

Making use of the selected extreme flows, the empirical extreme value distributions on high and low flows can be produced for the different scenarios. This allows a comparison of the improvement actions on the hydrological extremes.

An example of the empirical extreme value distribution of the peak flows and low flows is given in Figures 3 and 4 for scenarios 1, 2, 5 and 6 for the Demer at Hasselt.

It can be noticed that in general all the scenarios overestimate the peak flows. Scenario 1 gives the largest overestimation. When more rain gauges are used, a small improvement on the simulation of peak flows can be noticed (scenario 2). Also, when scenario 1 is compared with scenario 5, the use of more detailed ET data gives a significant improvement. When both improvement actions are combined in scenario 6, the extreme value distribution of the peak flows has the highest accuracy when comparison is made with the observations.

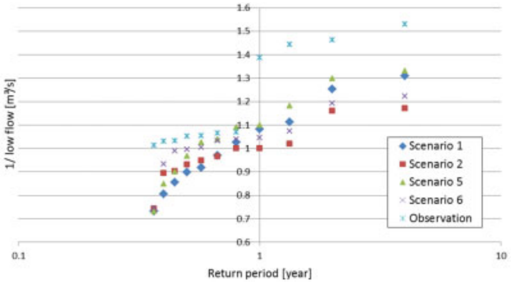

Figure 4. Empirical extreme value distribution of low flows for scenarios 1,2,5 and 6. Demer at Hasselt.

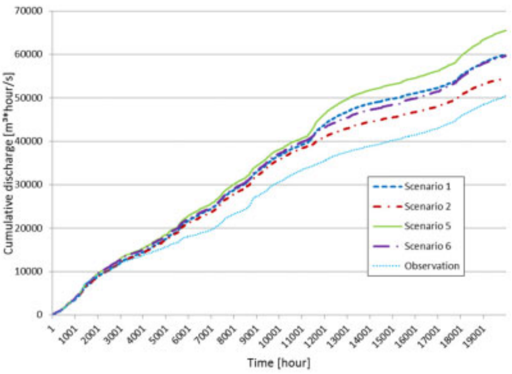

Figure 5. Cumulative flow volumes for scenarios 1, 2, 5 and 6. Demer at Hasselt. Starting date is 01/01/2002.

In Figure 4, the extreme value distributions of the low flows for the different scenarios show an overestimation when compared to the observations. For the lower return period (<1 year), the low flows are best modeled in scenario 6. Scenario 5 is best in modeling the low flows for the larger return periods (>1 year). Since scenarios 5 and 6 lead to the best extreme value distribution for low flows, it can be concluded that it is important to provide detailed ET data to enable accurate simulations of extreme low flows.

In Figure 5 the cumulative flow volumes for scenarios 1, 2, 5 and 6 are shown. In all the scenarios the cumulative flow volume is overestimated. The cumulative flow volume of scenario 2 approaches the most the cumulative flow volume of the observations.

From the three figures shown in this section it can be concluded that the hydrological model for this catchment can be further improved by taken into account the low flows and the cumulative flow volume.

In addition to this qualitative comparison a quantitative comparison has been performed, which is shown in the next section.

4.2 *Quantitative comparison*

In order to make a quantitative comparison Arheimer et al. (2011) propose to calculate the improvement between different model modifications. When using

Table 5. NSE for the different scenarios and catchments and the weighted mean NSE for the different scenarios.

Station ID and subcatchments	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Station 134: Demer Hasselt	0.42	0.70	0.30	0.74	0.54	0.74
Station 145: Velp Ransberg	0.75	0.39	0.36	0.65	0.77	0.45
Station 148: Zwartebeek Lummen	0.58	0.27	0.61	0.77	0.62	0.31
Station 152: Gete Halen	0.75	0.75	0.64	0.68	0.72	0.76
Station 161: Mangelbeek Lummen	−0.69	0.47	−0.79	0.61	−0.4	0.38
Station 163: Herk Kermt	0.73	0.67	0.61	0.67	0.73	0.73
Weighted mean	0.58	0.66	0.46	0.69	0.61	0.69

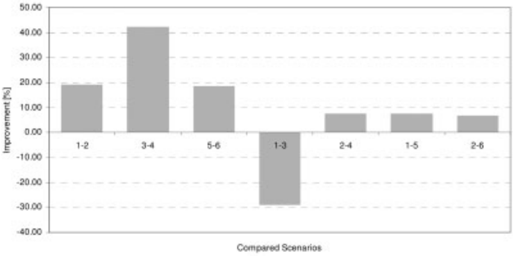

Figure 6. Improvement between the different scenarios on the rainfall-runoff generation, based on the mean NSE values.

the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) as fitness measure, the improvement I can be calculated as follows (Equation 1):

$$I = \frac{NSE_{ALT} - NSE_{REF}}{1 - NSE_{REF}} \tag{1}$$

where the subscripts of NSE refer to the reference and to the altered scenario.

To quantify the improvement actions of scenarios 1-6 on the rainfall-runoff (RR) generation, the NSE of simulated versus observed is calculated for the different scenarios and catchments (Table 5). This is done for the simulation period January 2002 to December 2005. To summarize the results, a weighted mean NSE is calculated for the different scenarios, using the relative size of the catchments as a weighting factor.

Figure 6 shows the improvement between the different scenarios based on the mean NSE values. To evaluate the use of more rainfall input data, the improvement between scenarios 1–2, 3–4 and 5–6 is calculated. When using NAM, the use of more rainfall data gives an improvement of about 19% and an improvement of about 42% is achieved when PDM is used. The use of more detailed ET input data is assessed by comparing scenarios 1–5 and 2–6. This gives improvements of about 7 to 8 %. To test which amount of improvement one can expect from the use of other model schematizations, scenarios 1–3 and 2–4 are compared. The respective improvements (−29% and 8%) are very different depending on the rainfall input. When only the HIC rain gauges are used as rainfall input, PDM performs badly. When both the HIC and RMI raingauges are used, PDM gives even better results in comparison with NAM. This means that PDM, in this case, is very dependent on the rainfall input, which can also be noticed when scenarios 3 and 4 are compared.

Next to the assessment of the improvements on the rainfall-runoff generations, also assessment of the hydrodynamic model output is done. For different gauging stations along the Demer river the observed and simulated water levels and discharges are compared for the different considered scenarios.

As mentioned in section 2.2, the InfoWorks model only covers the upstream part of the Demer river. This means that for scenarios 3 and 4 only a comparison can be made for the upstream gauging stations (Hasselt, Linkhout, Halen and Diest). The improvement in NSE between the different scenarios for the different locations is shown in Figures 7 and 8. The use of more rain gauges gives improvements in NSE, calculated for water levels, from 20 up to 50% when making use of NAM and Mike11. Also when PDM and InfoWorks-RS are used, improvements from 15 to 70% can be achieved, depending on the different locations. The comparison between NAM/Mike11 and PDM/Infoworks-RS is more difficult to make and depends on the location. It is clear that the water levels at Halen and Diest and the discharges at Diest have a much better accuracy in the Mike11 Model. The water levels at Hasselt have a much higher accuracy in the Infoworks-RS model with an improvement up to 80% in comparison with Mike11.

For the downstream gauging stations (Diest, Zichem and Aarschot) scenarios 1, 2, 5, 6 and 7 are simulated for the periods 01/12/2002 – 31/01/2003, 01/01/2004 – 31/01/2004 and 11/11/2004 – 30/11/2004. NSE is calculated and the improvements between the different scenarios are shown in Figures 9 and 10. The use of more raingauges does not give an improvement, except for the water levels at Zichem. This is in contrast with the previous findings on the RR results, where the use of more raingauges always gave a considerable improvement. This can be explained by the difference in simulation period between the RR model and the HD model. It does not mean that a positive improvement on long simulation period automatically gives a positive improvement on each considered subperiod. The use of more detailed ET is tested by comparing scenario 1 with 5 and 2 with 6. It is clear that for the

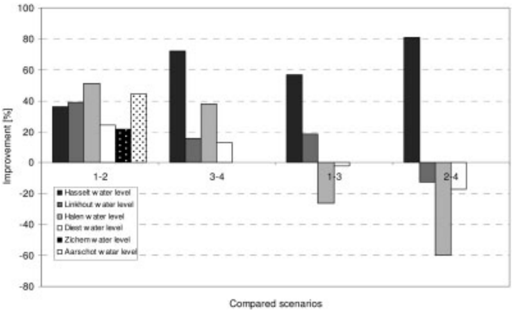

Figure 7. Improvement in NSE between the different scenarios for the upstream water level gauging stations along the Demer. (Simulation period 01/01/2002-01/07/2003).

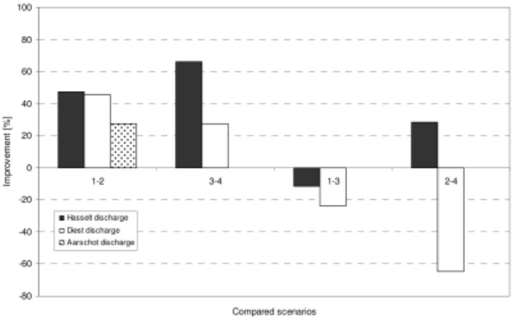

Figure 8. Improvement in NSE between the different scenarios for the upstream discharge gauging stations along the Demer. (Simulation period 01/01/2002-01/07/2003).

discharges it can give an improvement from 7 up to 25%, depending on the rainfall input. For the water levels at Zichem, the use of more detailed ET input data does not give an improvement, while the water levels at Diest are better modelled with the detailed ET data. When making use of more rain gauges also at Aarschot the water levels are better modelled with more detailed ET data.

By comparing scenarios 6 and 7 it is possible to assess the improvement of the model refinement at the Grote Steunbeer. It is clear that this model refinement has a positive effect on both the water levels and discharges. Improvements from 7 to 22% are achieved. Although model refinement was considered at only one place in the model, clear improvements can be noticed at different locations along the river.

By comparing scenario 1 with 6 and 1 with 7, the total improvement of the combination of the different actions can be calculated. The improvement actions on the input give total improvements from 5 up to 18%. A considerable additional improvement can be noticed when the model refinement at Grote Steunbeer is executed. The combined improvements are even larger than the sum of the separate improvements. This shows that it is not only important to have a look on the effect of the separate improvement actions, but also on the combination of different improvement actions.

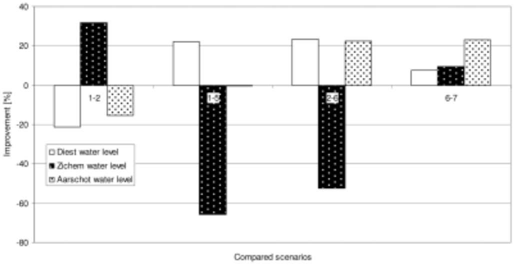

Figure 9. Improvement in NSE between the different scenarios for the downstream water level gauging stations along the Demer. (Simulation period 01/12/2002 – 31/01/2003, 01/01/2004 – 31/01/2004 and 11/11/2004 – 30/11/2004).

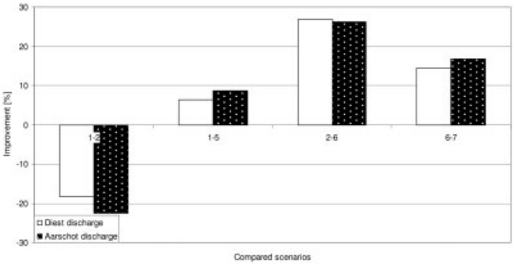

Figure 10. Improvement in NSE between the different scenarios for the downstream discharge gauging stations along the Demer. (Simulation period 01/12/2002 – 31/01/2003, 01/01/2004 – 31/01/2004 and 11/11/2004 – 30/11/2004).

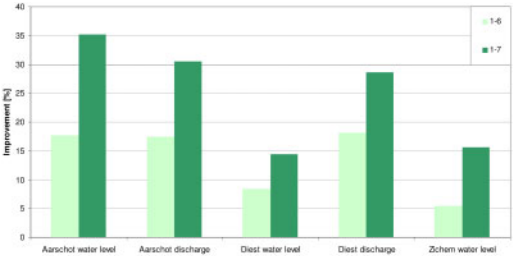

Figure 11. Total improvement in NSE for the downstream gauging stations along the Demer after input optimization (1–6) and after model refinement (1–7).

5 CONCLUSIONS

It is shown for the Demer river case that strong improvement of the rainfall-runoff submodel can be obtained by increasing the number of rain gauges. Also the use of more accurate evapotranspiration input can have a significant effect on the accuracy of the rainfall-runoff model results. For the river hydrodynamic submodel, two different schematizations have been tested, implemented in Mike11 and Infoworks-RS, and applied in combination with inputs obtained from two different rainfall-runoff models (NAM and PDM). After calibration, no significant differences were found between the results of the tested modelling packages. Improvements in the rainfall-runoff results, however, propagate through the system and lead to more accurate water level and discharge results. Also improvements in the implementation of the river regulation structures have a strong positive effect on the simulation results, hence increasing the predicting power of the hydrodynamic model.

It has been found that improvements on river discharges and water levels from 5 to 20% can be expected by using more accurate input data. Additional improvements from 5 to 15% can be achieved by more detailed modelling of the regulation structures.

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