5th Generation WAQUA Subdomain Models of Rijntakken

Deltares

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Keywords
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Summary
The 40-m Rijntakken grid “rijn40m_5-v1.rgf” is refined by a factor of 2 in M and N direction and used to create fine grid subdomain models for the River Rhine in the Netherlands. Based on the fine grid and on the BenO Baseline schematisation “beno13_5”, WAQUA subdomain models are created for the three River Rhine branches (Waal, IJssel, Neder-Rijn / Lek) and the bifurcation area (Splitsingspunten). The fine grid models:

- “beno13_5_20m_splp-v1”
- “beno13_5_20m_waal-v1”
- “beno13_5_20m_nrlk-v1”
- “beno13_5_20m_ijssel-v1”

are tested for stationary discharges at Lobith for as low as 600 m^3/s to 18,000 m^3/s. Though the subdomain models are not calibrated based on the fine grid, they compare well with the calibrated model (“beno13_5”).

We recommend using the fine grid models in analysis of the hydraulic effect of the interventions along the Rhine river; as the subdomain models are finer and allow more detailed schematisation of the measures.

When the effect of measures affects the discharge distribution, we don’t recommend using the branch models. In this case, we recommend using the Splitsingspunten model; Shall the interventions extend outside the Splitsingpunten model area, we recommend using the entire Rijntakken model.

For proper use of the WAQUA models, we recommend using the good modelling practice principles taking into consideration the assumptions and the limitations of the models as described in the report.

In this project, we devise as well an approach to create the Rhine River subdomain models in the future. This approach is presented and discussed further in report.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1.	Feb. 2015	Migena Zagonjolli		Mohamed Yossef		Johan Boon	
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Contents

1 Introduction

1.1 Purpose

The purpose of this report is to present the 5th Generation subdomain WAQUA models. The subdomain models are created and tested for each of the Rhine branches and the bifurcation area and are aimed to be used for assessing the hydraulic effect of the interventions in the context of permission grants. The models start from Emmerich in Boven-Rijn and cover the following respective areas (see Appendix A):

- Waal model - extending from Emmerich to Hardinxveld in the Waal including 1.8 km of Pannerdensch Kanaal (rkm 872.4).
- Neder-Rijn / Lek model - extending from Emmerich to Krimpen a/d Lek in the Lek, to upstream of Ooij polder (rkm 876.7) in the Waal and to Velp (rkm 884.8) in the IJssel.
- IJssel model - extending from Emmerich to Ketelbrug in the Ketelmeer, to upstream of Ooij polder (rkm 876.7) in the Waal and to rkm 882.5 in the Neder-Rijn.
- Splitsingspunten model - extending from Emmerich to Beneden-Leeuwen in the Waal (rkm 910.5), to downstream of the Nature area “de Blauwe Kamer” in the Neder-Rijn (rkm 908.5) and some 2 km upstream of Cortenoever in the IJssel (rkm 915.3).

In this report we refer to each of the branch models according to the main branch name, such as Waal, Neder-Rijn / Lek and IJssel model and to the bifurcation model as Splitsingspunten model. The WAQUA models are tested for the stationary conditions with inflows at Emmerich from as low as 600 m^3/s up to 18,000 m^3/s. In order to ensure that the discharge distribution is not influenced by new measures in the branch models, we impose a discharge boundary on the “cut” branch (short branch included in each of the branch models). For the Splitsingspunten model, the QH-relations defined at the downstream boundaries allow for evaluating the effect of the interventions on the discharge distribution along the branches. Nevertheless, for the interventions that influence the discharge distribution and cannot be modelled with or do not fall within the Splitsingspunten model, the entire Rijntakken model need to be used.

1.2 Background

To compute water levels, flow rates, and the hydraulic effect of the measures to be implemented along the Rhine branches, RWS uses the 2D modelling package Simona.

The existing BenO[1] Simona Rijntakken model (Driessen and van der Sande, 2013) is based on a 40-meter computational grid. In order to better represent the interventions, often a finer grid is needed and hence constructed. The finer models are created by refining the grid of the Rijntakken model at the area of interest; sometimes refining the entire model is required. The latter procedure is preferable to ensure uniformity within projects. In this project, we create fine grid models for each of the branches and Splitsingspunten area separately. This allows obtaining the required level of details, in a standardised manner, and within acceptable computational time.

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[1] BenO (Beheer en Onderhoud) models are used for assessing the hydraulic effect of the interventions in the context of permission grants.

1.3 Organisation

The work was carried out by Migena Zagonjolli (Deltares). Tijmen Vos, Dénes Beyer (RWS-ON) and Martin Scholten (RWS-VWL) contributed to this work with their fruitful discussions and suggestions. The intensive discussions with Tijmen Vos were truly appreciated and led to continuous improvements of the created models. Colleagues from the Deltares Software team contributed to this project with their adaptations of the software when required.

2 Methodology

In this chapter, we describe the method that has been used for creating the WAQUA subdomain models of the river Rhine in the Netherlands. During the project execution, several other alternatives have been tried to solve different problems. In this chapter, we provide the recipe for creating subdomain models in the future, based on the lessons learned during this project. In the following chapters we highlight the challenges faced and the methods used in dealing with them.

2.1 Extent of WAQUA models

At the beginning of the project, RWS-ON has provided indicative locations for model boundaries (email of Tijmen Vos, 31 May 2013). Based on these indicative locations, and further analysis, the final locations of the model boundaries were chosen. The final choices have been made based on the following considerations:

- Topography near the indicative locations (presence of weirs, sharp bends, water bodies). The boundary location should be free from structures, in straight reach, and avoid cutting through water stagnant bodies.
- Position of the discharge cross sections that are used for estimating the Nikuradse roughness of the main river channel. The discharge cross sections related to the roughness reaches present in the model should be as well present in the model.
- Same MN grid line numbering in the overlapping areas of the subdomain models. The grid node M=1 and N=1 should be present in all models.

Based on the above-mentioned criteria, the final choices of the boundaries locations are given, in terms of fine grid N-line, in Table 2.1.

Table 2.1 Subdomain model boundary locations (given as fine grid N-line number).

Model	Boundary location
Waal	boundary at Pannerdensch Kanaal on N = 1204
Neder-Rijn / Lek	boundary at Waal on N = 1412 boundary at IJssel on N = 1877
IJssel	boundary at Waal on N = 1412 boundary at Neder-Rijn on N = 1721
Splitsingspunten	boundary at Waal on N = 3079 boundary at Neder-Rijn on N=3031 boundary at IJssel on N = 3151

Here we note that, the Neder-Rijn / Lek model boundary at the IJssel lead to relocation of the discharge cross section “Q-IJsselkpDoesbbrg” (used for computing main channel roughness) further upstream (from grid line N=1877 to N=1873). In this way, the Q-section is present within the model. The boundary location at the IJssel was unavoidable due to the presence of weirs and of the high Koppenwaardse dam, which limited the choices in close vicinity. The relocation of the discharge cross section is done only in the Neder-Rijn / Lek model. In the other domain models, the discharge cross section is kept at the original location.

2.2 Model construction approaches

One can use several approaches to create the WAQUA domain models based on the Baseline schematisation of the Rhine branches (referred hereafter as Rijntakken schematisation). The following approaches are all possible:

1. Creating subdomain grids and then projecting the Rijntakken Baseline schematisation on the subdomain grids;
2. Creating subdomain section (“sectie”) features (in Baseline) while keeping intact the rest of Rijntakken Baseline schematisation and fine grid;
3. Creating the subdomain Baseline schematisations and converting those to WAQUA using the Rijntakken fine grid; or
4. Keeping the Rijntakken Baseline and fine grid model intact, while using domain enclosure file (“.rrb”).

The first method was considered to be the most optimal for this project. This decision was taken based on the following:

- Same Baseline schematisation will be used for the coarse grid models and fine grid subdomain models. The presence of only one Baseline schematisation is preferable to avoid discrepancies between the schematisations and it is better for maintenance.
- In this case, the WAQUA model is only projected on the subdomain grid extent, not on all the grid.
- The fine grid of Rijntakken is too large, reducing the flexibility of further use, such as memory issues in Baseline. Using the subdomain grids is more feasible.

In this project, the Rijntakken Baseline schematisation of “beno13_5-v1” (Driessen and van der Sande, 2013) was used to create the domain WAQUA models using the domain grids.

2.3 Grid construction

All subdomain models include the entire Boven-Rijn; and three of the models include the entire Pannerdensch Kanaal. To ensure that all models are having the same MN coordinates in the overlapping area, the M=1 and N=1 node is present in all of the models (Figure 2.1). This means that all domain grids and models are extending in the Waal downstream to the node M=1 (see Figure 2.1).

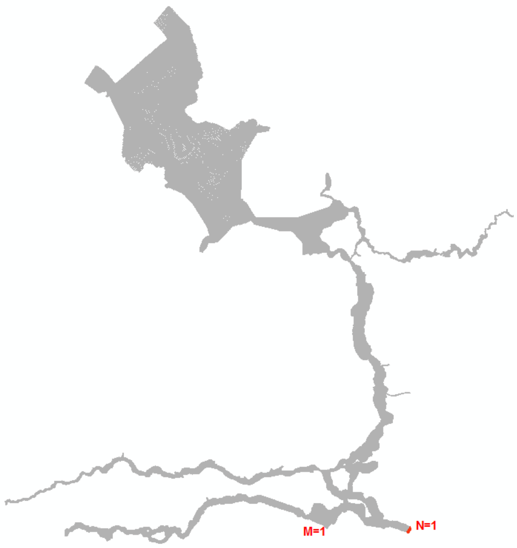


Figure 2.1 The M=1; N=1 location of Rijntakken grid.

The 40-m Rijntakken grid “rijn40m_5-v1.rgf” is refined by a factor of 2 in M and N direction. The resulting 20-m Rijntakken grid “rijn20m_5.rgd” was then cut to cover the extent of the subdomain models, ensuring that the overlapping areas have the same M&N numbering. Cutting of the grids is done in a manner that during the conversion to WAQUA the generated enclosures fit to the location of the downstream boundaries and no manual modifications are necessary. Thus, the (M=1, N=1) point in the 40-m grid is as well (M=1, N=1) point in the 20-m grid of all four models. No other modifications were made to the grids. Table 2.2 provides the names of the generated grids and their characteristics.

Table 2.2 Name of the fine 20 m grids.

Name of the Grids	MxN
Rijn20m_5-v1	1479 x 9059
Rijn20m_waal_5-v1	957 x 5609
Rijn20m_nrlk_5-v1	1333 x 6927
Rijn20m_ijssel_5-v1	1479 x 8479
Rijn20m_splp_5-v1	1333 x 3150

The current modelling practice of Rijkswaterstaat for the Dutch rivers utilises the modelling software package WAQUA. As WAQUA is a two-dimensional depth-averaged modelling system, local three-dimensional features like flow over weirs, groynes, barriers, etc., cannot be resolved. These are often modelled using sub-grid schematisation using a weir or weir-like formulation. The effect of the weir on the flow is parameterized in the form of an energy loss term in the momentum equation. In the present subdomain model schematisations, which employ grid cell sizes of 10 to 20 m, we may consider that the current WAQUA sub-grid approach for weirs is still applicable. It is, however, advised to test this consideration as it has been suggested in the Deltares memo of de Goede and van Kester (November, 2013) attached to this report (see Appendix D).

2.4 Improvements to Baseline schematisation

In this project, the Rijntakken Baseline schematisation of “beno13_5-v1” was used to create the WAQUA models. However, during model testing it was found out that projection of the Baseline schematisation on the fine grid resulted in, what we considered to be, inappropriate WAQUA model schematisations, which had to be adjusted. Below is a list of these issues:

1. Stuw Driel: The two structure lines representing the Stuw Driel are projected onto different N-grid lines. Figure 2.2 shows the way the Baseline feature of Stuw Driel (given with green colour line) is projected on the fine grid (two black lines extended onto two different grid lines. Moreover, some erroneous thin dams are created. This was resolved through a model measure (“rt_stuw40m_a1”) created by RWS-ON shown in Figure 2.2 on the right.
2. Hondsbroeksche Pleij: The initial projection of the Hondsbroeksche Pleij on the fine grid was not optimal. This lead to water going through on the left side of the structure due to some opening created during conversion to fine grid (see Figure 2.4). As a result, the discharge distribution between the Neder-Rijn and IJssel was not as expected. RWS-ON created the model measure “nr_rwhp40m_a1” to make the Hondsbroeksche Pleij measure fitted to the new fine grid (Figure 2.4).

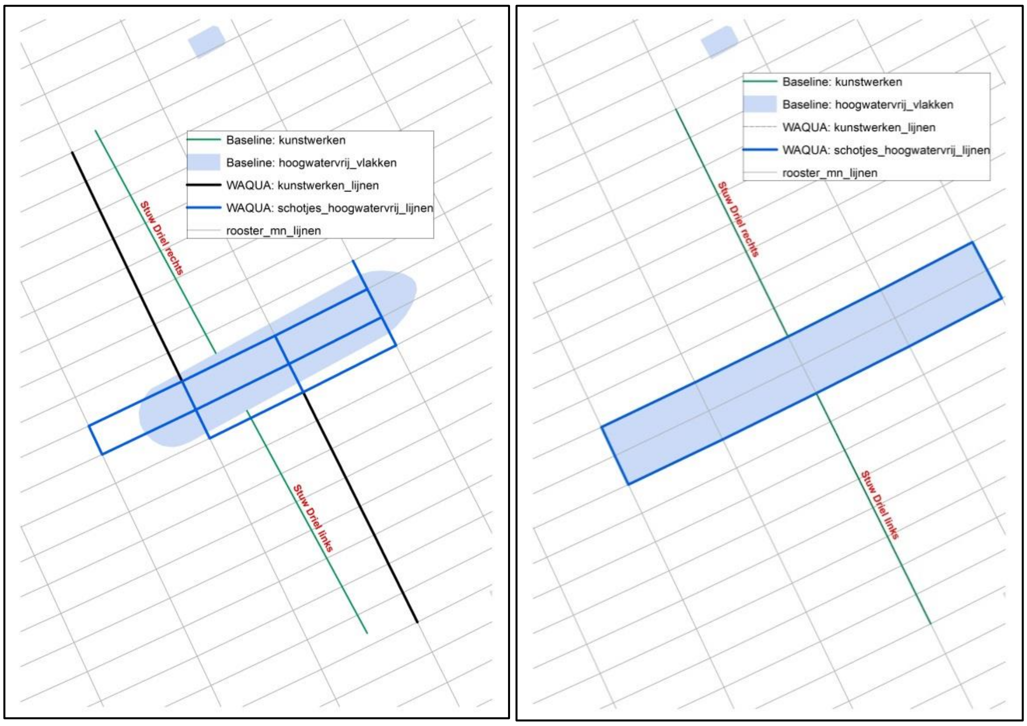


Figure 2.2 Projection of Driel structure on the fine grid before (on left) and after modifications to the schematisation (on the right).

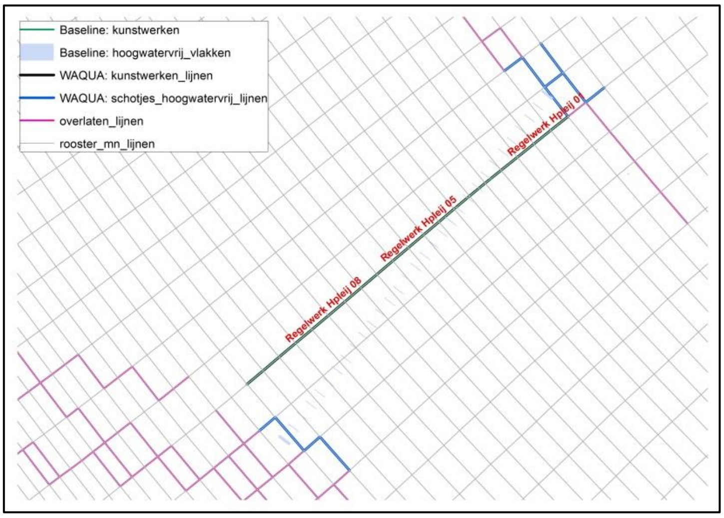


Figure 2.3 Projection of Hondsbroeksche Pleij structure on the fine grid before modifications to the schematisation.

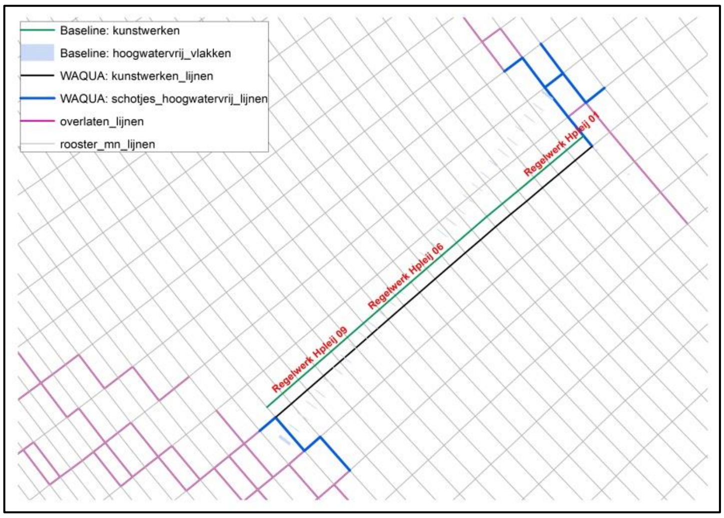


Figure 2.4 Projection of Hondsbroeksche Pleij structure on the fine grid after modifications to the schematisation.

3 "Sectie" feature: During this project it was noticed that during conversion to WAQUA, several erroneous thin dams ("schotjes") were created on the border of the main channel and at the groyne fields, mostly parallel to the flow and in some locations perpendicular to it. This was caused due to very tiny "donut" polygons present in the "sectie" feature. Currently, Baswaq (Riza, 2005) includes a routine (bw0406, see below) which leads to creation of thin dams when the "sectie" feature has tiny "openings".

> --
> *0400 bw0406*
> *Doel van de routine*
>
> *Vanwege de eisen die gesteld worden aan een rrb is het mogelijk dat kleine delen van de rrb niet goed worden weergegeven. Hierin is voorzien door de berekende rrb aan te vullen met schotjes. Op deze wijze wordt recht gedaan aan het principe van de rrb, namelijk het niet mogelijk maken van stroming in de betreffende cellen. In eerste instantie worden de lijnen volledig naar het rooster vertaald. Vervolgens worden in bw0407 op basis van irrbgr enkel de juiste schotjes gebruikt; er hoeven geen schotjes te komen staan op plaatsen waar de rrb al voldoet.*
>
> *Rol van de routine in het proces*
>
> *Het omzetten van zowel de buiten- als de eilandpolygonen naar lijnen op het rekenrooster.*
> --

A possible modification to the present routine is to make an additional check that no "schotjes" are created far from the enclosure (as in our case). This issue was reported to the Baswaq developers. For this project, RWS-ON has corrected the "sectie" feature to avoid the presence of tiny "donuts". Thus, the erroneous thin dams are no longer present in the Baseline schematisation and the WAQUA models created within this project.

Except for the Neder-Rijn / Lek model, the computations for the other domain models were carried out with the manually adjusted WAQUA input files and only afterwards a new WAQUA model was created based on the improved Baseline schematisation.

4 Water bodies ("plassen") and WAQINI: WAQINI (executable for creating the initial water level fields in the main river channel and water bodies) handles the water bodies (Baseline feature "plassen") on the following manner:

It intersects the feature "plassen" with "rooster_ws_vlakken" and creates the "plascel.asc" file that consists of

M,N, "*Maaiveldhoogte",* "*Plasoppervlakte binnen de cell",* "*oppervlakte van de rooster cell".*

If the water body ("plas") occupies less than 50% of the grid cell area, WAQINI gives to this cell the "dry" status. Otherwise, the water level in the cell equals the elevation of the surrounding ground ("maaiveldhoogte").

When the "plas" consists of several adjacent features with same "maaiveldhoogte" and "ruwheidscode" (see Figure 2.5), those cells might still result as "dry" since currently WAQINI considers each features separately. Below follows an example of the "plassen" near Hagestein (in the "sluiscomplex"). The "plas" is represented with two features as indicated in Figure 2.5 with dark and light blue colour. Both features have same "maaiveldhoogte" and roughness ("ruwheidscode"). WAQINI checks the "Plasoppervlakte binnen de rooster cell" and the "oppervlakte van de rooster cell" for each features separately. Thus, the two grid cells surrounded by a red line, will be treated by WAQINI separately. Since none of these features fulfils the 50% occupation requirement (see Table below) those two cells will incorrectly be given the "dry" status. These cells will withdraw water from the surrounding cells in the follow up computation.

As it is shown in Table below, WAQINI creates two records for each grid cell considering each "plas" feature separately.

M	N	Maaiveldhoogte	Plasoppervlakte binnen de rooster cell	Oppervlakte van de rooster cell.
532	4873	4.50	45.896702	104.698904
532	4873	4.50	46.631659	104.698904
535	4873	4.50	45.614250	103.630250
535	4873	4.50	49.340698	103.630250

This issue can be solved by first dissolving the neighbouring polygons (based on "Maaiveldhoogte") before carrying out the intersection with the "rooster_ws_vlakken". Note, that this solution will not fully solve the problem when the "maaiveldhoogte" of adjacent "plassen" is different. In that case, one can think of other solution, such as lowering the margin for which a cell is considered to be wet.

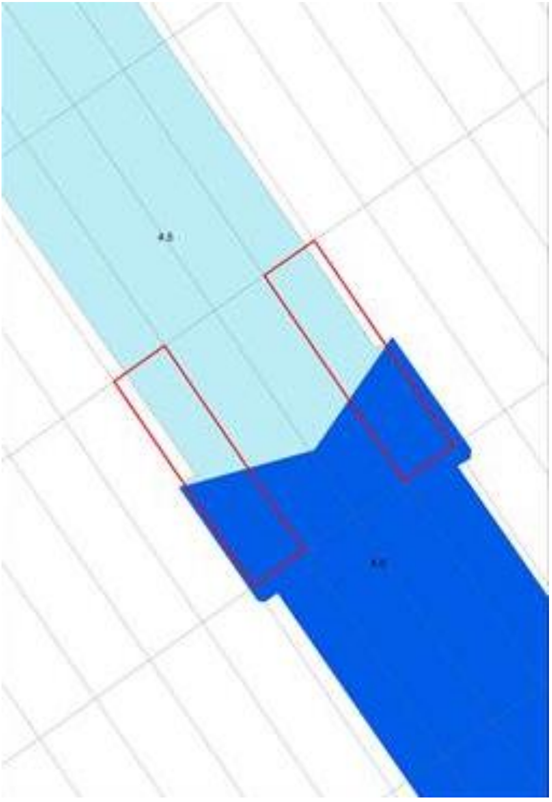


Figure 2.5 Extent of the feature "plassen" in comparison to the (grey coloured) fine grid lines.

Currently, there are discussions regarding the necessary modifications to the WAQINI procedure to solve, among others, the issue mentioned above. For this project, the WAQINI water level field was adjusted to correctly represent the initial water level field in the water body area (see Figure 2.6).

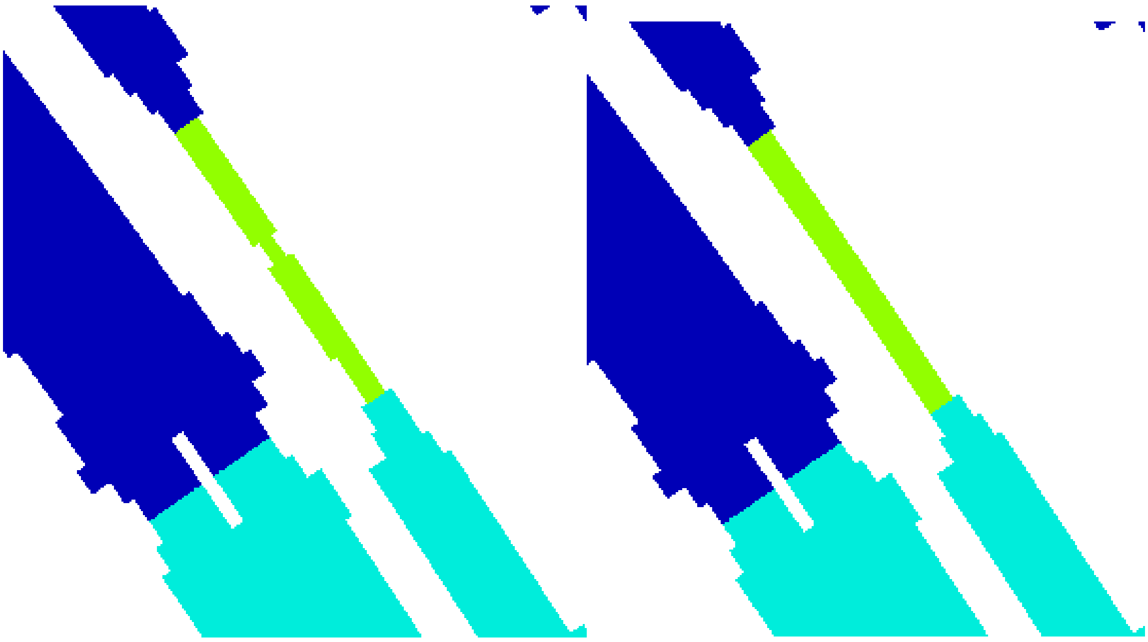


Figure 2.6 Extent of the feature "plassen" near "Sluiskomplex Hagestein" after WAQINI (on the left) and after manual modifications (on the right side).

2.5 WAQUA model modifications

Apart from the adaptations and modifications to the Baseline schematisation, some additional modifications were made to the WAQUA subdomain models compared to the existing coarse grid “beno13_5” Rijntakken model:

2.5.1 Hydraulic Structures

Regulating bifurcation structures

At the bifurcation, there are two hydraulic structures which can influence the discharge distribution between the Rhine branches. However, at the branch models, the discharge distribution is controlled by the defined boundary at the “cut” branch. To ensure compatibility between the structure operation and the defined discharge distribution in the branch models, it was decided to keep the structures of Pannerden and Hondsbroeksche Pleij fixed at the position computed from the Splitsingspunten model for all branch models. The initial tests with Splitsingspunten model have shown that the free operation of these structures leads to other discharge distribution between the branches. A fixed position of the structures in the Splitsingspunten model will allow for evaluating the influence of the measures (in the Splitsingspunt model area) in the discharge distribution. That is another reason why structures are considered fixed in the final computations with Splitsingspunten model.

For RWS it is important that the control structure at the bifurcation “Regelwerk Pannerden” provides the requested discharge distribution in the BenO (Beheer en Onderhoud) models used for issuing permission grants (vergunningverlening). For the discharge distribution between the Pannerdensch Kanaal and the Waal is valid the discharge distribution for MHW condition of 16,000 m^3/s at Lobith. That aims at a discharge of 10,165 m^3/s at the Waal. With the Splitsingspunten model and the stationary computation of 16,000 m^3/s at Emmerich including the respective laterals, the position of the Pannerden Regelwerk which leads to the required discharge distribution between the Waal and the Pannerdensch Kanaal is found out. This structure position is then used for all other computations with the Splitsingspunten model and the branch models for discharges equal or lower than 16,000 m^3/s. Same procedure is used for the 18,000 m^3/s discharge at Emmerich. Table 2.3 gives the discharge distribution as defined in the policy (“Beleidsmatige Afvoerverdeling”) for 16,000 m^3/s and 18,000 m^3/s discharge at Lobith (including stationary lateral of 6 m^3/s at Gemaal Kandia at Pannerdensch Kanaal). Table 2.4 gives the optimal position of the Regelwerk Pannerden and Hondsbroeksche Pleij in the Splitsingspunten model for which the desired discharge distribution is obtained for 16,000 m^3/s at Lobith.

Table 2.3 Policy Discharge Distribution (Beleidsmatige afvoerverdeling).

Lobith	Waal	Pannerdensch Kanaal	Neder-Rijn	IJssel
16000	10165	5835	3380	2461
18000	11758	6242	3380	2868

Table 2.4 The computed position of the structures for the 16,000 and 18, 000 m^3/s.

Lobith	Sill Position		Waal	Pannerdensch Kanaal	Neder-Rijn	IJssel
	Pannerden	Honds. Pleij				
16000	14.08	14.509	10165.85	5834.62	3381.31	2458.48
18000	17	11	11655.01	6347.94	3453.28	2899.35

The computation results given in Table 2.4 show that:

- The discharge distribution for 16,000 m^3/s at Emmerich is closer to the desired distribution though the IJssel still gets some 2 m^3/s less.
- The Waal cannot withdraw the desired portion of discharge for 18,000 m^3/s at Emmerich even though the structure at Pannerden is fully closed while the Neder-Rijn still receives more discharge although the structure of Hondsbroeksche Pleij is fully open.
- The Hondsbroeksche Pleij is not fully closed for 16,000 m^3/s discharges as it is expected and defined in the policy of the structure, while it is fully functioning for discharge of 18,000 m^3/s. Keeping the structure closed for 16,000 m^3/s discharge would likely lead to extra discharge to Neder-Rijn.

It is important to note that the position of the structures needs to be determined once again for the new (yearly) subdomain models. Moreover, RWS might reconsider the operation rules for the bifurcation structures to be applied for the subdomain models in the future, such as for example:

- Fix Regelwerk Pannerden to the position which ensures the legal discharge distribution while the Hondsbroeksche Pleij is then not fully closed, but in operation. This method is applied currently.
- Allow a small deviation from the legal discharge distribution and fulfil to the condition that the Hondsbroeksche Pleij does not operate for discharges equal or lower than 16,000 m^3/s.

Adjusting operation speed of Hondsbroeksche Pleij

It is necessary that the computations are stable. The initial computations with the Rijntakken “beno13_5” model showed an unstable behaviour of the Hondsbroeksche Pleij structure. That meant that the structure schematisation in WAQUA needed to be adjusted, namely the speed with which the structure moved needed to be optimised.

During this project some test computations were carried out with the fine grid Splitsingspunten model to find out the optimal operating speed (“snelheid”) of Hondsbroeksche Pleij which would lead to a stable operation of the structure. Computations were carried out for the stationary discharge of 16,000 m^3/s and with operating structure. As it can be seen in Figure 2.7 , for a speed of 0.00010 m/s, one receives a stable operation of the structure. Thus for this project, this speed is used instead of the value of 0.0009 m/s, which has been applied so far (for consistency, we have adjusted this in the 40-m grid model as well). This means that the structure moves slower than previously. The new moving speed for Hondsbroeksche Pleij coincides to the one used for the Regelwerk Pannerden.

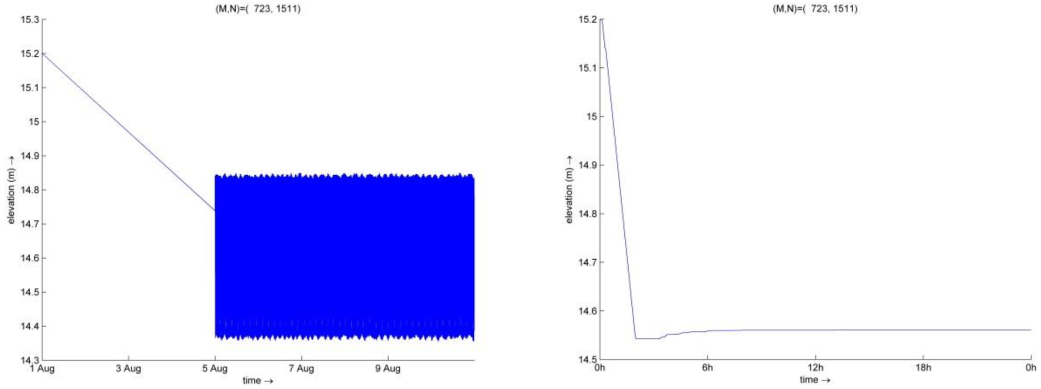


Figure 2.7 Influence of structure moving speed in the Hondsbroeksche Pleij structure stability (left: speed=0.0009 ms^{-1}; right: speed=0.0001 ms^{-1}) given as sill depth on time.

Operation rules for the Hondsbroeksche Pleij

The operation rules as originally created by Agtersloot (2012) include that one of the 30 structure openings is open during the discharges lower than 10,000 m^3/s. The 11th opening from the river side with a width of 5 m is considered open for the environmental reasons. During this project, the barrier opening operating for the purpose of environmental flows were considered as the other barrier openings for all the discharges smaller than 16,000 m^3/s. Thus, in technical terms, the operation rules of the single barrier B13 of the coarse grid is changed to the following:

was

```
B13: SILL_DEPTH     INITIAL =  11.00 VELOCITY = 0.00090
              GATE_HEIGHT    INITIAL = 999.00
              BARRIER_WIDTH  INITIAL =   0.316
              CONDITION
                 IF  ((DISCHARGE:C921  LT  9990)  AND  (DISCHARGE:C915  LT  3379))
THEN
                    TB102 DISCHARGE: C921
                 ELSEIF  ((DISCHARGE:C921  LT  9998)  AND  (DISCHARGE:C915  LT
3379)) THEN
                    TB103 DISCHARGE: C921
                 ELSEIF (DISCHARGE: C915 LT 3379) THEN
                     TB100 DISCHARGE: C915
                 ELSEIF (DISCHARGE: C915 GT 3381) THEN
                     TB100 DISCHARGE: C915
                 ELSE
                     FIXED_STATE
                 ENDIF
```

becomes

```
B13: SILL_DEPTH     INITIAL =  15.20 VELOCITY = 0.00010
     GATE_HEIGHT    INITIAL = 999.00
     BARRIER_WIDTH  INITIAL = 0.316
     CONDITION
        IF (DISCHARGE: C915 LT 3379) THEN
            TB100 DISCHARGE: C915
        ELSEIF (DISCHARGE: C915 GT 3381) THEN
            TB100 DISCHARGE: C915
        ELSE
            FIXED_STATE
        ENDIF
```

This change is implemented in the Rijntakken “beno13_5” model as well as in all WAQUA subdomain models created within this project.

Fixed position of Stuw Driel
During low discharge computations, the three structures at Neder-Rijn / Lek operate according to defined operation rules. The initial computations for 600 m^3/s at Emmerich showed that the Driel structure is very sensitive to minor changes in flow conditions (such as water levels) leading to a situation where different stable stationary solutions are obtained for the same upstream inflow. Thus, the water levels in Neder-Rijn / Lek reach though stable can be lower or higher than in the other models (coarse model or Splitsingspunten model) and even different in consequent computations. To ensure that the same stable stationary solution is achieved, it was decided to fix the sill position of Stuw Driel to be at the same position as in Splitsingspunten model for same discharge computation. More details follow in Chapter 3.3.

It was as well concluded that the current regulation rules (Agtersloot, 2012) are not sufficient for low stationary discharge computations at Neder-Rijn. For stationary low discharge computations, modified regulation rules are necessary in the future.

2.5.2 Adaptations to the WAQUA SIMINP files

In this project, few additional modifications were made to the input files of the models:

- Two extra Q-sections were added for the RvdR projects at Lent and Veessen-Wapenveld:
  - Q High flood channel Lent M=242-263, N = 1741
  - Q High flood channel Veessen M=707-773, N= 5957
- The operation rules for the Regelwerk Pannerden ("*sturingtabel"*) are included in a separate file and no longer in the SIMINP.
- Definition point barriers Hondsbroeksche Pleij is modified in the SIMINP as well as in the "kunstwerk-p" file in order to introduce an ordering of the point barriers in WAQUA model that follows the Baseline schematisation point order.

2.6 Hydraulic Conditions

2.6.1 Boundary conditions in general

For all models the upstream boundary type is a permanent discharge defined at Emmerich. For each model the computations are carried out for stationary discharges of 600, 1020, 2000, 4000, 6000, 8000, 10000, 16000, and 18000 m^3/s. The discharge distribution over grid cells is done automatically using the option 'automatically' for the upstream boundary. Thus, the user-specified total discharge is distributed in an automatic manner over the grid cells along the opening, accounting for local water depth and bottom friction.

For the Splitsingspunten model, the three downstream boundaries are Qh-relations. The Qh-relations of the Splitsingspunten model are constructed based on the computations with the coarse grid Rijntakken model with the upstream stationary discharge boundaries as given above.

At the downstream boundaries of the three branch models, at Hardinxveld, Krimpen a/d Lek and Ketelbrug, we used the Qh-relations as in the Rijntakken "beno13_5-v1" WAQUA model.

The branch models have a fixed discharge distribution, thus, a discharge boundary is defined at the "cut" branch. There are several options to define the discharge at the "cut" branches:

1. Get discharge time series out of the calibrated fine grid Rijntakken model. This model is not yet available.
2. Get discharge time series out of the coarse grid Rijntakken model.
3. Get discharge time series out of the fine grid Splitsingspunten model.

The last option was used in this project. This way, the branch models will have the discharge distribution of the fine grid model. Moreover, all subdomain models will have same discharge distribution. The discharge was defined per cell along the river cross section (including winter bed) and not as a cumulative discharge per one cross section. The stability of the boundaries was tested for different ranges of discharges.

2.6.2 Qh-relation for the Splitsingspunten model

The Qh-relations for the downstream boundaries of the fine grid Splitsingspunten model are created based on the computations with Rijntakken WAQUA model “beno13_5-v1”. Several stationary computations were carried out for upstream discharges of 600, 1020, 2000, 4000, 6000, 8000, 10,000, 16,000, and 18,0000 m^3/s. In these computations, the structures at bifurcation were operating according to the defined “stuwsturing” rules, thus, they had no fixed position for discharges equal or higher than 16,000 m^3/s at Lobith.

The boundaries of the Splitsingspunten model extend on the coarse grid “rijn40m_5-v1.rgf” N-lines as given in Table 2.5. At those locations, water level and discharges were recorded for every computation.

Table 2.5 Location of the downstream boundaries of the Splitsingspunten model given as N-line of “rijn40m_5.rgf” grid.

Model	Boundary locations
Splitsingspunten model	Waal branch on N = 1540, rkm 910.5 Neder-Rijn branch on N=1516, rkm 908.5 IJssel branch on N = 1576, rkm 915.3

In these computations an outflow at Amsterdam Rijnkanaal was defined for the discharges lower than 2000 m^3/s. As it can be seen in the results of Table 2.6, a lateral Q=-12.5 m^3/s at Amsterdam Rijnkanaal (ARK) for low upstream discharges is not appropriate. Afterwards, it was decided to abandon the discharge at ARK for inflows at Emmerich of less or equal to 1020 m^3/s.

Table 2.6 Computed Qh-relation for the Splitsingspunten WAQUA model.

	Waal, N=1540		**Neder-Rijn, N= 1516**		**IJssel, N=1576**	
$Q_{Emmerich}$	Q	H	Q	H	Q	H
600	479	2.220	2	5.999	119	3.129
1020	793	3.178	26	5.999	200	4.140
2000	1439	4.648	238	6.167	339	5.677
4000	2743	6.835	732	6.185	556	7.629
6000	4096	8.345	1103	7.909	847	8.511
8000	5390	9.199	1547	9.057	1126	8.979
10000	6502	9.783	2119	9.764	1455	9.357
16000	10177	11.630	3391	10.889	2534	10.164
18000	11699	12.349	3446	10.934	2958	10.498

As it can be seen from Table 2.6, the “beleidsmatige afvoerverdeling” is not obtained in the computations where the “Regelwerk Pannerden” is operating according to the regulation rules. Some 12 m^3/s more discharge enters the Waal during 16,000 m^3/s computation and during 18,000 m^3/s computation the Waal cannot withdraw the desired discharge of 11,758 m^3/s. Based on these computation results, it was decided to keep the position of these structures fixed in the following model computations. The sill position of Regelwerk Pannerden is regulated in order to ensure the desired discharge distribution between the Waal and the Pannerdensch Kanaal for 16,000 m^3/s at the Emmerich.

Considering that the fine grid models will be tested for the same range of discharges for which the Qh-relation is valid, it is possible that the defined Qh will be insufficient in case the discharge distribution is different in the fine grid models leading to different discharge distribution for the two extreme discharges of 600 m^3/s and 18000 m^3/s. Some attention has to be paid to this limitation of the Qh-relation when used for the extreme discharges of 600 m^3/s and 18,000 m^3/s.

2.6.3 Discharge boundaries for the branch models

In WAQUA there are several methods to define the discharge that is leaving the system via the “cut” river branch, such as:

1. Open boundary with automated discharge distribution. This means that the discharge is defined as a total discharge for a cross section and then it is automatically converted to discharge per cell based on the Chezy formula. Unfortunately, this option does not work very well in WAQUA and based on previous experience of the author is considered to be unstable. Accordingly, it was not considered in this project.
2. Open boundary with manual discharge distribution. This means that the discharge is defined per grid cell.
3. Closed boundary with local discharge extraction through Discharge (“bronnen”) and Source (“putten”) option.

The second approach was considered to be the most robust and it is therefore used in this project. Though this procedure is similar to the third approach (discharge is defined per cell), it was considered that defining the open boundary was more appropriate to the simulated conditions. The discharge to be extracted is computed from computations with the Splitsingspunten model.

2.6.4 Laterals

All computations are carried out including the stationary laterals for each upstream discharge. The set of laterals for discharges of 6.000 m^3/s and higher (except 18,000 m^3/s) is created by Beyer (2012) using “HR2006_4” WAQUA model. The laterals for lower discharges are scaled based on the laterals belonging to the 6.000 m^3/s discharge. Reader is referred to Beyer (2012) for more information.

For this project, the lateral values belonging to discharges above 1020 m^3/s were taken out of Beyer (2012), see Appendix B. For 600 and 1020 m^3/s discharges, it was initially proposed to use an outflow of 12.5 m^3/s at Amsterdam-Rijnkanaal (ARK). This caused instability in the model runs where the inflow to Neder-Rijn was lower than the outflow at ARK. Later, it was decided to consider no laterals at Neder-Rijn / Lek branch for the low discharges of 600 m^3/s and 1020 m^3/s. Same set of laterals as for 16,000 m^3/s were considered for the 18,000 m^3/s discharge.

2.6.5 Initial fields

For all models, an initial computation with upstream discharge of 600 m^3/s was carried out using some general water level setting for the model. Based on this computation result, the WAQINI generated water level field was used for the follow up lengthy computation, which aimed to ensure stable flow conditions in the model. In order to reach stationary conditions in the water bodies that were initially either over or under filled with water, long computation times were required.

The SIMONA fields of water levels and velocities created during the lengthy computation run were used as initial condition for the final computations of 5 days.

The above procedure proved insufficient for 600 m^3/s discharge at Neder-Rijn / Lek model. For the computations with low discharges, with the moving structures, computations are extremely sensitive to changes in the structures positions. It is sufficient for one of the Neder-Rijn / Lek structures to move to get a new stationary stable situation. The Simona initial fields consist of water level and velocity fields, but do not include information regarding the structures, thin dams etc. The use of RESTART option was then considered. However, though providing better and faster stable solution, even this option was not found optimal for our problem. At the end, it was decided that for the 600 m^3/s discharge computation with Neder-Rijn model, a simulation period of 60 days should be applied using the WAQINI water level fields as initial fields. At the end of the 60 days computation, a stable solution is obtained.

2.7 Numerical parameters

In principle, refining of the computational grid would prompt the necessity of recalibration of the model. Within this project the recalibration of the fine Rijntakken model was not carried out. Thus, the summer bed roughness values resulting from the calibration of the coarse grid model were assumed as well appropriate for the fine grid domain models. The only model parameters which were subject to alteration were the time step and eddy viscosity.

Another parameter which was subject to analysis was the parameter ThetaC. The parameter ThetaC is a weighing factor that is used in the determination of the energy loss over the weir. Depending on the value of ThetaC, the energy loss of the previous time step is not included (ThetaC = 0.0) or partially included (ThetaC between 0 and 1) or fully included (ThetaC = 1.0) in the computation of energy loss at current time step. A high value of ThetaC ensures a stable flow pattern, but also results in a slower (or completely absent) adjustment of the flow pattern. In our stationary computations, both values of the ThetaC provide the same solution. However, the computation with ThetaC=0.95 takes much longer computation time compared to same computation with ThetaC=0.60. Based on the experience with these type of models, RWS-ON recommended using a ThetaC=0.95 for the fine grid models instead of the ThetaC=0.60 used for the coarse grid models.

The numerical time step and viscosity for the fine grid models was determined based on test computations with the Splitsingspunten model. The test computations are carried out with the Splitsingspunten model for the 16,000 m^3/s discharge and reported in details in Section 3.1.1. The selected parameters:

- Time Step = 0.10 min (Δt =0.25 min is used for coarse grid models)
- Eddy Viscosity =1 m^2/s (same as for coarse grid models)

are used for all fine grid models.

2.8 Software and software adaptations

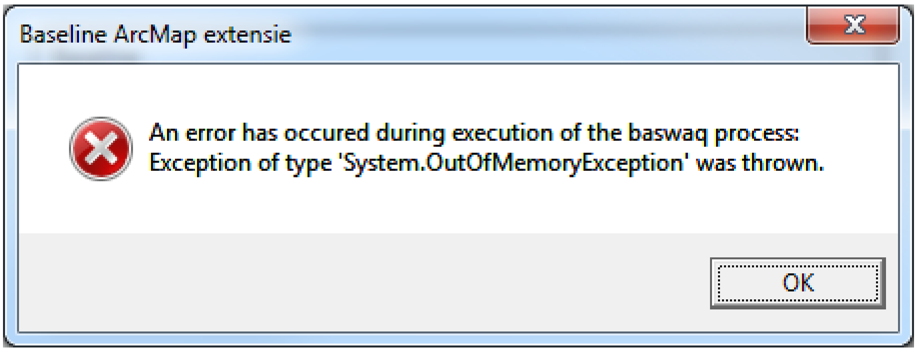
Table below provides information regarding the software used for this project. However, due to software limitations sometimes ad-hoc executable are being developed and used for the project. This is described below.

Software	Version
Baseline	5.2.1.658
ArcGis	9.3.1 (Built 1850)
Delft3D RGFGRID	4.20.00.34496
Simona	2012 (Linux 64-bit environment; partitioning in two i7 nodes)

2.8.1 Limitations due to working with the large number of grid cells

During the project, the following constraints were faced when working with the fine grid:

- It was not possible to convert the grid onto geodatabase feature of the fine grid of the IJssel model. The Baswaq function “Convert RGF file” failed with the error message shown below. The id-number to be included in the file 'roos-id.asc' was too big for the format string used.
-



Action: This project led to adaptation of the “Baswaq.exe” to deal with large number of grid cells. The changes to the code are included in the Baseline versions succeeding the one used in this project.

- During the execution of the project, the conversion to WAQUA of the fine Rijntakken grid ended up before creation of the “invoer.gdb” due to a known memory issue:

Action. This issue was reported and to the author’s knowledge it is solved in the most recent versions of Baseline.

- Due to the large number of grid cells present in the IJssel or Rijntakken fine grid models, it was not possible to post process the results using the WAQVIEW of Simona 2012 in Windows-XP environment. This is due to buffer constraints in the official executable.

Action: For this purpose a special WAQVIEW of the Simona2013 release was made. The file “Waqview.bat” was specially adjusted in order to be able to visualise large matrix (grid) SDS-files. The modification included a change in defined length of the buffer array IBUFFR. This meant a change of ILNBUF = 20000000 to ILNBUF = 35000000. This problem does not occur with Simona 2014 installed in Windows7 environment.

2.8.2 "Aangetakte plassen" in Baseline and WAQUA projection

In Baseline schematisation (Figure 2.8), the water bodies connected to the river and considered as "Aangetakt", can be fully isolated from the main river when projected to the WAQUA coarse grid or still have a connection to the river in the fine grid model.

Currently WAQINI considers these water bodies similar to the ones that are on the floodplain, thus, here the initial water level relates to elevation of the surrounding floodplain ("Maaiveldhoogte"). There is an on-going discussion whether the water bodies connected to the river should be considered by WAQINI differently. Here one should still pay special attention to the "aangetakte plassen" located on floodplain and which might not be connected to the river during low flow scenarios.

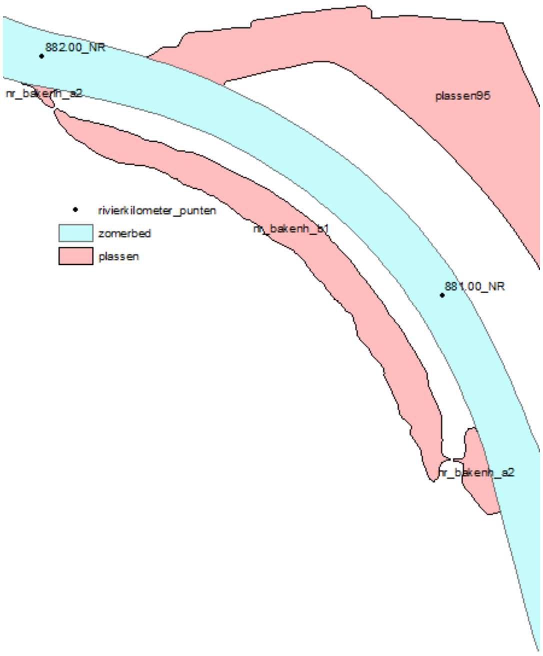


Figure 2.8 Example of water bodies connected to the main river channel in the Baseline schematisation.

2.9 Approach guidelines

In this section we summarise in general lines the approach applied for creating the WAQUA subdomain models.

- WAQUA models are based on the BenO Baseline schematisation "beno13_5-v1".
- The Rijntakken 40 m coarse grid is refined by a factor of 2 in both M and N directions (2x2) and then cut to cover the subdomain model area. Accordingly, separate models are created.
- The Baseline schematisation of the Rijntakken is projected in the subdomain fine grids in order to create the corresponding WAQUA models.
- All models are tested and compared with the overall 40-m grid model for stationary discharges at Emmerich of 600, 1020, 2000, 4000, 6000, 8000, 10000, 16000, and 18000 m^3/s. For every discharge equal or higher than 2000 m^3/s is used a set of laterals which is created by RWS-ON (Beyer, 2012). For lower discharges, there are no laterals assumed. For 18,000 m^3/s the lateral discharges belonging to 16,000 m^3/s are used.
- Downstream the Splitsingspunten model is used Qh-relation computed with the coarse grid Rijntakken model.

- Downstream the branch models, at Hardinxveld, Krimpen a/d Lek and Ketelbrug, are used the Qh-relations belonging to the Rijntakken model.
- At the other boundaries (of the “cut” branches) is defined a discharge boundary which is computed with the fine grid Splitsingspunten model. Discharge is computed and defined per grid cell.
- Numerical parameters of ThetaC and time step are different from the coarse grid model. Upon request of RWS-ON, ThetaC =0.95 is used for the fine grid models. The optimal time step for the fine grid models is defined after several test computations with the Splitsingspunten model for Q=16,000 m^3/s. The defined time step is used for all fine grid models.
- At the bifurcation, the structures of Regelwerk Pannerden and Honsbroeksche Pleij have an influence on the discharge distribution if they don’t have a fixed position. Therefore, the structures of Regelwerk Pannerden and Hondsbroeksche Pleij are having a fixed position in the final computations. Their fixed position is determined based on the test computations with the Splitsingspunten model:
  – With the Splitsingspunten model for a discharge of 16,000 m^3/s (including laterals) is the position of the Regelwerk Pannerden adjusted to provide the policy discharge distribution (“beleidsmatige afvoerverdeling”). This structure position is used for all other computations with Splitsingspunten and branch models for discharges lower than and equal to 16,000 m^3/s.
  – The structure of Hondsbroekse Pleij ensures that the flow to Neder-Rijn does not exceed 3380 m^3/s for discharges above 16,000 m^3/s at Emmerich. For lower discharges at Emmerich the structure should be closed according to the policy (“vastgestelde beleid”), which BenO models are supposed to comply. In this project, the structure is adjusted so that no more than 3380 m^3/s goes to Neder-Rijn and this position is used for all other computations with branch models and for low discharges.
  – For the 18,000 m^3/s discharge, the Regelwerk Pannerden is fully closed while Honsbroeksche Pleij is fully open.
- The weir at Driel during the low discharge computations (of less than 4000 m^3/s) with Neder-Rijn / Lek model does not operate according to the operation rules, but has a fixed position. The weir position is determined by the respective computations with the Splitsingspunten model.

The subsequent sections describe in more details the applied approach and the reasons for the made choices.

2.10 Computation procedure

For all domain models, lengthy computations were carried out with a ThetaC=0.60. The water level and velocity fields of the lengthy computation were used as initial condition for the final computation of same discharge with ThetaC=0.95 or as initial field for the successive discharge level computation. Depending on the discharge level, a stationary condition along the river and floodplains (including water bodies) is obtained after a lengthy computation period of 20 to 60 days.

Some water bodies take a lot of time to fill in or to reach the stable water levels. Here one can manually define the water levels fields directly in SIMINP in order to limit the computation time. However, it is desired to correct the Baseline schematisation and/or adapt the WAQINI procedure in order to deal with the issue of empty of overloaded water bodies currently present in our schematisations.

The final computation with ThetaC=0.95 was carried out for a simulation period of 5 days. Since the computations with ThetaC=0.95 take much longer time, one saves computation time using this two-step method. A deviation from this method is done for the computations of low discharges with Neder-Rijn / Lek model. The reason for this deviation is detailed in Chapter 3.3.

2.11 Computation Workflow

Below we summarise the computation workflow used in this project:

1 Obtain the Qh relations for the Splitsingspunten model. Carry out computations for all ranges of discharges with the coarse grid Rijntakken model recording the discharge and the water levels at the cross sections corresponding to the boundary lines of the Splitsingspunten model.
2 Carry out the 16,000 m^3/s computation with Splitsingspunten model in order to
   - define the optimal time step;
   - identify any potential discrepancy in the model due to the conversion to the fine grid;
   - check whether the defined downstream boundaries work properly.
3 With the accepted Splitsingspunten model carry out the computations for all other ranges of discharges recording the discharge per cell at the location where the boundaries of the “cut” branches are defined in the branch models.
4 Carry out the 16,000 m^3/s computation with the Waal model in order to
   - identify any potential discrepancy in the model due to conversion to the fine grid;
   - check whether the defined downstream boundaries work properly.
5 With the approved the Waal model carry out the computations for all other ranges of discharges.
6 Repeat steps 4 and 5 for the Neder-Rijn / Lek and IJssel model successively (not in parallel). First the boundary at the Waal has to be tested with one of the models.

Thus, first the computations with Splitsingspunten model are carried out and only after acceptance of the model, the computations with branch models were carried out. Those were carried out consecutively. Once one branch model was accepted, thus the boundary locations found optimal, the computations with the other branch models were carried out. For all models, first the computation of 16,000 m^3/s discharge was carried out and analysed. After successful performance of this model, the other ranges of discharges were tested.

2.12 Analysis procedure

The procedure used to analyse computation results can be summarised in following actions:

Discharge distribution. Discharge distribution between branches for different ranges of discharges is compared with the required discharge distribution (according to “Maatgevende Afvoerverdeling”) as well as with the one obtained from the computations with the Rijntakken coarse grid model and with the Splitsingspunten model.
Model stability. Computations are considered stable when there are no fluctuations in water levels in the two last recorded water level maps and no discharge fluctuations present in the recorded river kilometer discharge cross sections.
Water level comparisons. Computations carried out with the subdomain models are compared with the coarse grid Rijntakken model computation results, referred hereafter as Rijntakken model. The computation results of the branch models are also compared with the Splitsingspunten model results. The aim is to have small water level differences between the

Rijntakken model and the fine grid domain models. For the 16,000 m^3/s computation, a difference of maximum 5 cm is considered as acceptable.

The comparison between model results is done taking into account the following:

- Discharge distribution in the branches. More discharge to a particular branch would most likely result in higher water levels.
- Output locations (river kilometre points) are projected in 20 m (lengthways) distance and/or 10 m crossway distance leading to a deviation caused by the output location position. This can be of influence when comparing the absolute water levels.
- Projection to the fine grid is different from the coarse grid and in some locations this projection can be of high influence for the discharges of equal or less than 6,000 m^3/s.
- Extent of the weirs and the crest elevation can be different in coarse and fine grid models. Sometimes this difference can be at the marge of causing flooding or no flooding of some area.

3 Computations with subdomain models

In this chapter we describe the computation results for all subdomain models as well as the applicability and limitations on the use of these models.

3.1 Splitsingspunten model "beno13_5_20m_splp-v1"

3.1.1 Optimal time step

With the created Splitsingspunten WAQUA model "beno13_5_20m_splp-v1", the analysis regarding the optimal numerical time step and eddy viscosity is made. This involved several stationary computations of 16,000 m^3/s with varying values of time step and eddy viscosity. Table 3.1 presents the computations carried out for this analysis. In those computations the sill depth of the Regelwerk Pannerden is considered at the fixed position of 14.13 m. With this position of Pannerden Regelwerk, the discharge entering the Waal is found to be 10,162 m^3/s in all computations (except for the computation with lower viscosity of 0.5). The discharge at Neder-Rijn is 3,344 m^3/s while the discharge entering the IJssel is 2,493 m^3/s. The Hondsbroeksche Pleij does not operate during the 16,000 m^3/s computation. Note that these settings differ from the final selected settings to be used for the models and reported in Table 2.4.

Table 3.1 List of computations carried out with Splitsingspunten model "beno13_5_20m_splp-v1".

Run	Δt (min)	VISC	THETAC
param_000	0.25	1.00	0.6
param_001	0.166666667		
param_002	0.10		
param_003	0.05		
param_004	0.166666667	0.50	

With the first four tests (param_000 to param_003) computations one evaluates the influence of the computational time step during the MHW condition. If there are no (or very small) differences in the water levels between the computations with Δt_i and Δt_j then the Δt_i is considered to be the optimal time step. Considering twice refining of the grid, a twice lowering of the eddy viscosity value was tested.

The model runs showed that the discharge distribution between the Neder-Rijn and IJssel in the fine model is different from the coarse model. In these simulations, some 30 m^3/s extra discharge is entering the IJssel in comparison to the "beleidsmatige afvoerverdeling". This is explained by the incorrect schematisation of the Hondsbroeksche Pleij in the fine grid model. As it was explained in Section 0, the structure extended in Baseline schematisation according to the coarse grid lines, but when converting to the fine grid model, some openings remain on the left side of the barrier. The extent of the barrier in the fine model is manually modified in the computation "param_001hpleij". For the final computations with Splitsingspunten model, a WAQUA file was delivered by RWS-ON to correct schematisation of Hondsbroeksche Pleij on the fine grid models.

The computation with low eddy viscosity of 0.50 lead to even further deviation of the discharge distribution compared to the “beleidsmatige afvoerverdeling”. Based on this it was concluded to keep eddy viscosity unchanged for fine grid computations (eddy viscosity =1). Table 3.2 shows the discharge distribution in all computations. Note that these computations were carried out without laterals.

Table 3.2 Discharge distribution in Rhine branches (Splitsingspunten model).

Computation	Waal	Neder-Rijn	IJssel
param_000	10161	3344	2493
param_001	10162	3345	2493
param_001hpleij	10166	3355	2480
param_002	10162	3345	2494
param_003	10163	3344	2493
param_004	10145	3350	2506

The runtime of the computations is provided in Table 3.3. The computations with time step of 6 seconds and 3 seconds take relatively long time to be finalised. In all these computations, one i7 node of Deltares Linux cluster was used.

Table 3.3 Computation time of the carried out simulations.

	Computation time (min)	Simulation time (min)	ST/CT
param_000	515.00	14400	28
param_001	792.00		18
param_002	**1739.00**		8
param_003	**2169.00**		6
param_004	832.00		17

The time step variation led to water level differences of up to 5 mm in the river axis (see Figure 3.1 to Figure 3.3). Taking into consideration the computation (Wall clock) time as well, the time step of 0.10 minutes was considered as appropriate for the fine grid models. This decision was justified by the following:

- Changing the time step from 10 sec to 6 seconds had small effect on the computed water levels (Table 3.4);
- Further lowering of the time step had no significant influence on the water levels;
- The time step of 0.10 min can easier be related to input and output settings such as simulation time or post-processing time;
- Further lowering of the time step leads to larger computation time, which is not justified by the sufficient gain in accuracy.

Table 3.4 Analysis of the water levels on the river axis. Comparison is done with the lowest time step computation (param_003).

Simulation	Time step (min)	Average (m)	Maximum (m)	Minimum (m)
param_000	0.25	-0.0023	0	-0.0051
param_001	0.166666667	-0.0015	0.0006	-0.0045
param_002	0.10	-0.0006	0.0006	-0.0021
param_003	0.05	-	-	-

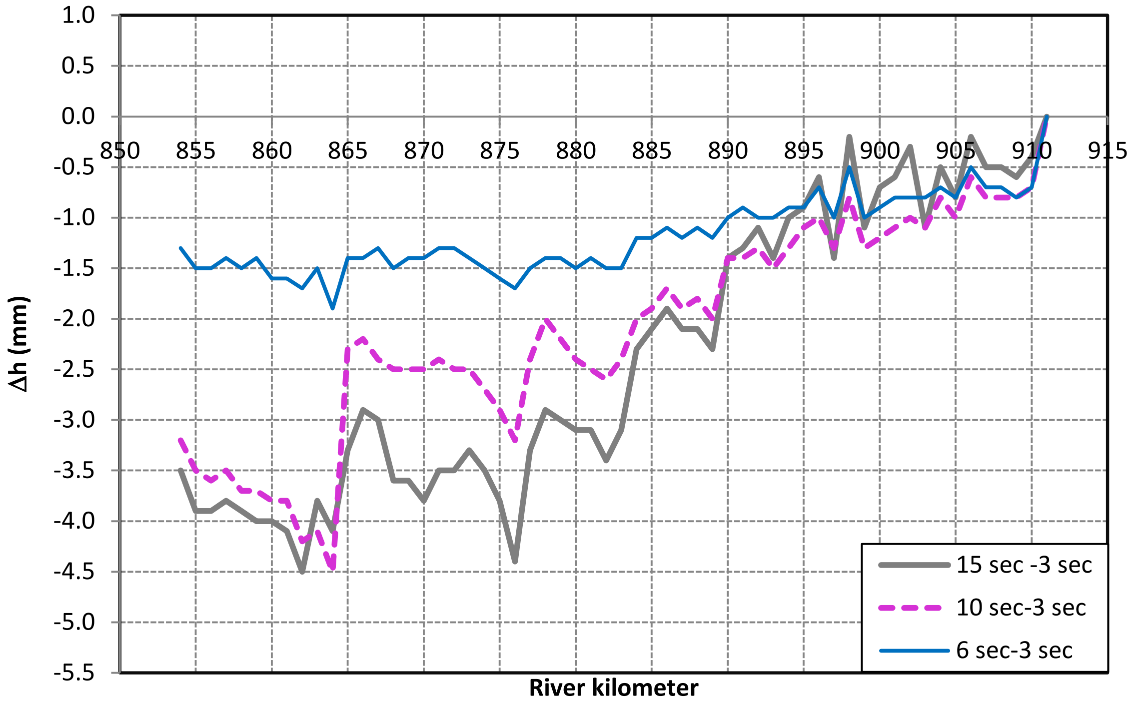


Figure 3.1 Water level differences for different computation time steps (seconds) in the Boven-Rijn and Waal.

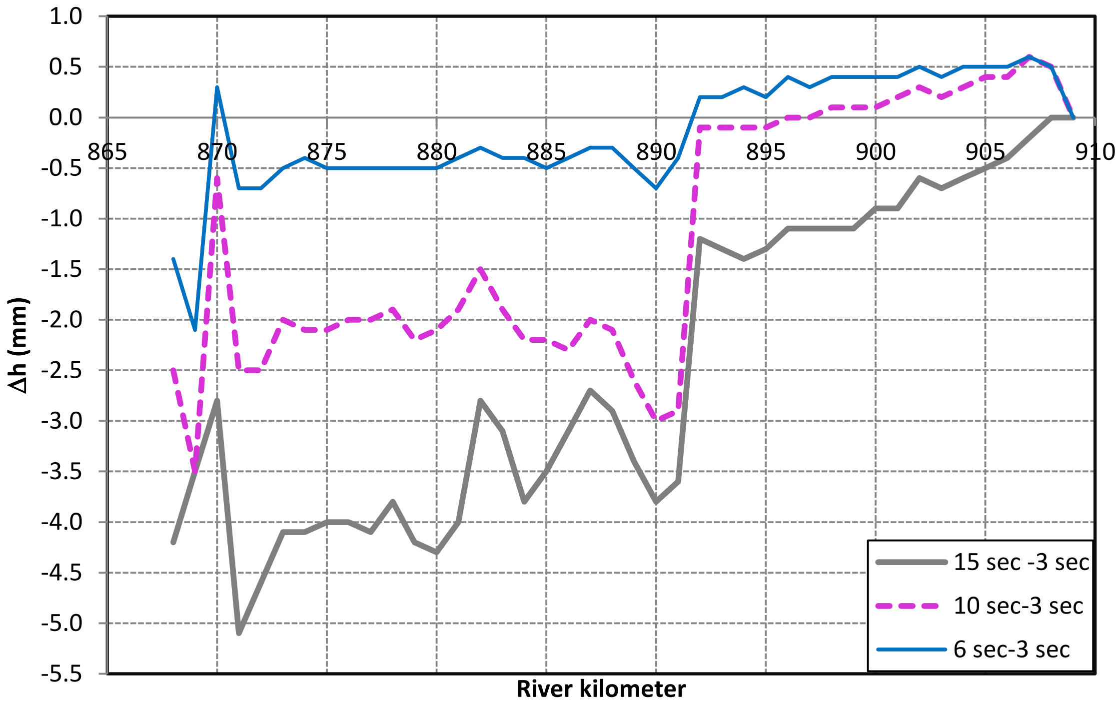


Figure 3.2 Water level differences for different computation time steps (seconds) in the Pannerdensch Kanaal and Neder-Rijn / Lek.

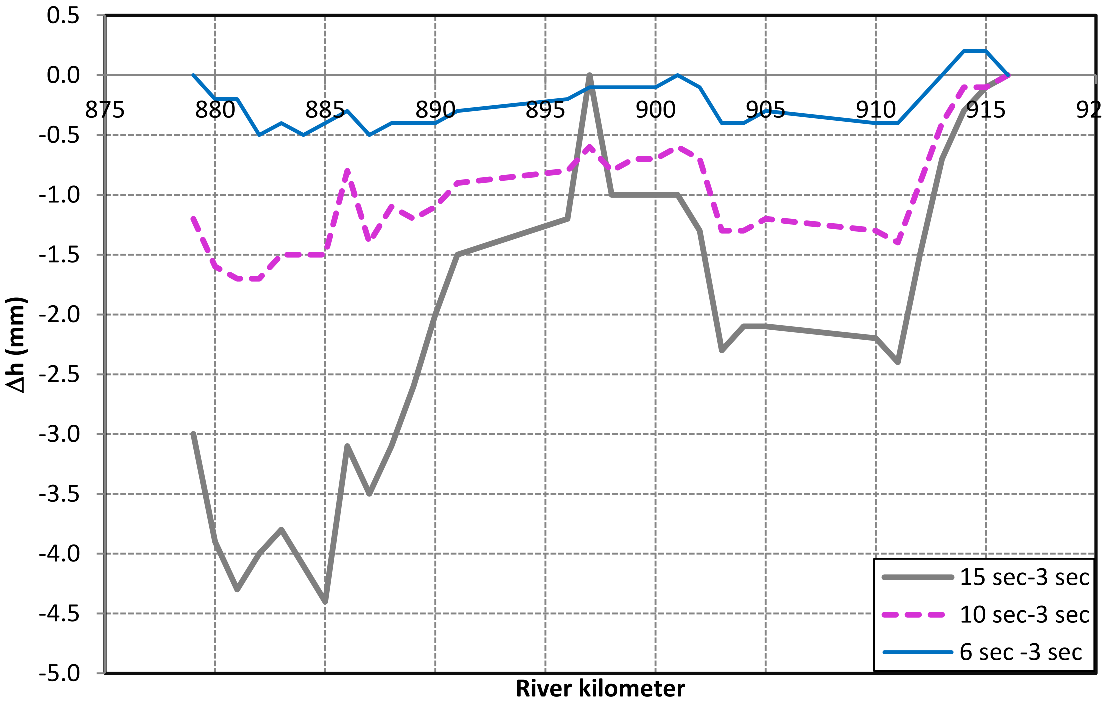


Figure 3.3 Water level differences for different computation time steps (seconds) in IJssel

3.1.2 Stationary computations with Splitsingspunten model

With the chosen time step and the defined Qh-relation at the boundaries, the stationary computations for all ranges of discharges were carried out. In these computations, the bifurcation structures operated according to the operation rules.

At the end of the final 5 days computation with this model, a stable situation was reached. Table 3.5 shows the computed discharge near the locations where the downstream boundaries of the Splitsingspunten model are defined. For 18,000 m^3/s discharge computation, the Neder-Rijn and IJssel branch receive more discharge than in the Rijntakken model. The Qh-relation does not cover the new ranges of discharges leading to incorrect water levels at the boundaries of the Splitsinspunten model.

Table 3.5 Discharge distribution in Rijntakken and Splitsingspunten model given at the location near the downstream boundaries. In grey are shadowed the computations when the discharge differences between two models are about 10 m^3/s or more.

Q	Model	910.00_WA	908.00_NR	915.00_IJ
600	Rijntakken	478.55	2.58	118.99
	Splitsingspunten	479.76	4.27	116.19
1020	Rijntakken	793.59	26.38	200.03
	Splitsingspunten	795.30	28.38	196.28
2000	Rijntakken	1438.71	238.20	338.67
	Splitsingspunten	1442.25	247.69	325.50
4000	Rijntakken	2743.10	731.89	555.58
	Splitsingspunten	2767.43	717.94	545.72
6000	Rijntakken	4096.14	1103.03	847.13
	Splitsingspunten	4095.31	1099.83	851.24
8000	Rijntakken	5389.98	1546.72	1126.14
	Splitsingspunten	5383.52	1545.96	1133.25
10000	Rijntakken	6502.15	2118.38	1454.99
	Splitsingspunten	6506.30	2112.19	1457.74
16000	Rijntakken	10177.08	3391.19	2534.18
	Splitsingspunten	10176.00	3392.60	2534.03
18000	Rijntakken	11698.81	3445.64	2958.22
	Splitsingspunten	11662.94	3461.58	2977.91

Figure 3.4 to Figure 3.6 and Table 3.6 show the water level differences between the Rijntakken coarse grid model and the Splitsingspunten fine grid model for all branches. The computations results can be summarised as following:

General observations

- All computations are stable at the end of the 5 days simulations with ThetaC=0.95.
- The measuring point of Pannerdensche Kop falls dry in the 600 m^3/s computation.
- The initial water levels at the “aangetakte plassen” is based on the “maaiveldhoogte” which is much higher than the water level in the main channel during low discharge computations. Meanwhile, there are water bodies located on the floodplains with open connection to the river (“aangetakte plassen”), which do not have a direct connection with the main river in the WAQUA model. Thus, while for these water bodies the current WAQINI procedure might be appropriate, the procedure is not appropriate for the water bodies having the open/wide connection with the main river channel. In the future, it is important to think of some adaptation of WAQINI procedure making a differentiation between two types of “aangetakte plassen”.
- The emptying of the water bodies takes place very slowly.

Discharge Distribution

- The discharge distribution between all branches in Splitsingspunten model is significantly different for two discharge conditions of the 4000 m^3/s and the 18,000 m^3/s compared to the Rijntakken model. This deviation is not caused by the operation of the structures at bifurcation since those are operating in the same way in both computations: Pannerden is fully closed and Hondsbroeksche Pleij is fully open in 18000 m^3/s computation.

- Discharge distribution in the Splitsingspunten and Rijntakken model are similar for 16,000 m^3/s computation. However, the operation of the structures according to the operation rules does not ensure the policy discharge distribution given in Table 2.3. As mentioned before, afterwards it was decided to fix the position of the structures in order to ensure the policy distribution between branches.
- The IJssel and Neder-Rijn receive higher discharge at the Splitsingspunten model compared to the Rijntakken model. The extra discharge is not supported by the used Qh-relation (see Table 2.6). The extra discharge has to still be accommodated with the same water level (as a result of extrapolation). Thus, there is a need to enhance the Qh-relation for inflow levels higher than 18,000 m^3/s as well as for lower than 600 m^3/s.

Water levels

- On average, the water levels in the Splitsingspunten model differ from the Rijntakken model with less than 5 cm; except in computations with inflow discharges less than 4000 m^3/s. In those computations the deviation reaches up to 15 cm. In these cases the discharge distribution between the branches Neder-Rijn and IJssel in the Rijntakken and Splitsingspunten model is significantly different, and as expected, also shows large deviation in water level.

Table 3.6 Analysis of the water levels on the river axis. Comparison between Splitsingspunten and Rijntakken model.

	600	1020	2000	4000	6000	8000	10000	16000	18000
Average	0.03	0.03	0.02	0.02	0.01	0.00	0.00	0.00	0.00
Maximum	0.09	0.09	0.08	0.07	0.03	0.02	0.02	0.02	0.03
Minimum	0.00	-0.04	-0.15	-0.09	-0.02	-0.03	-0.02	-0.03	-0.04

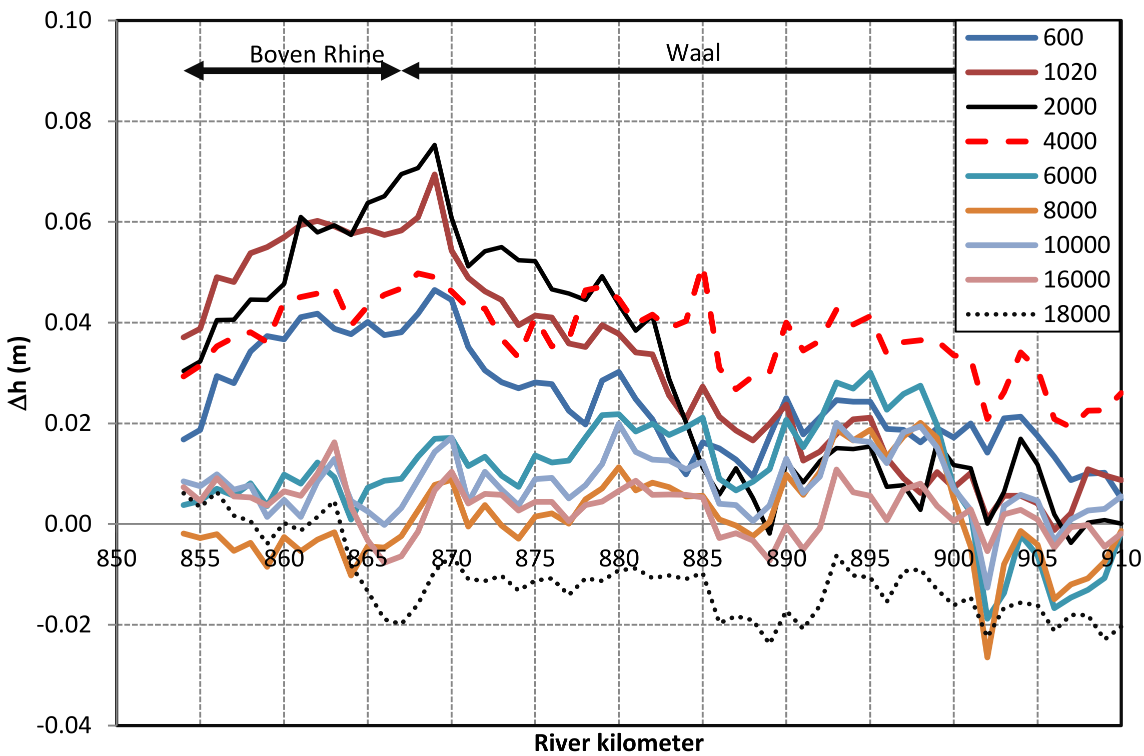


Figure 3.4 Water level differences between Splitsingspunten and Rijntakken model given as (Splitsingspunten-Rijntakken).

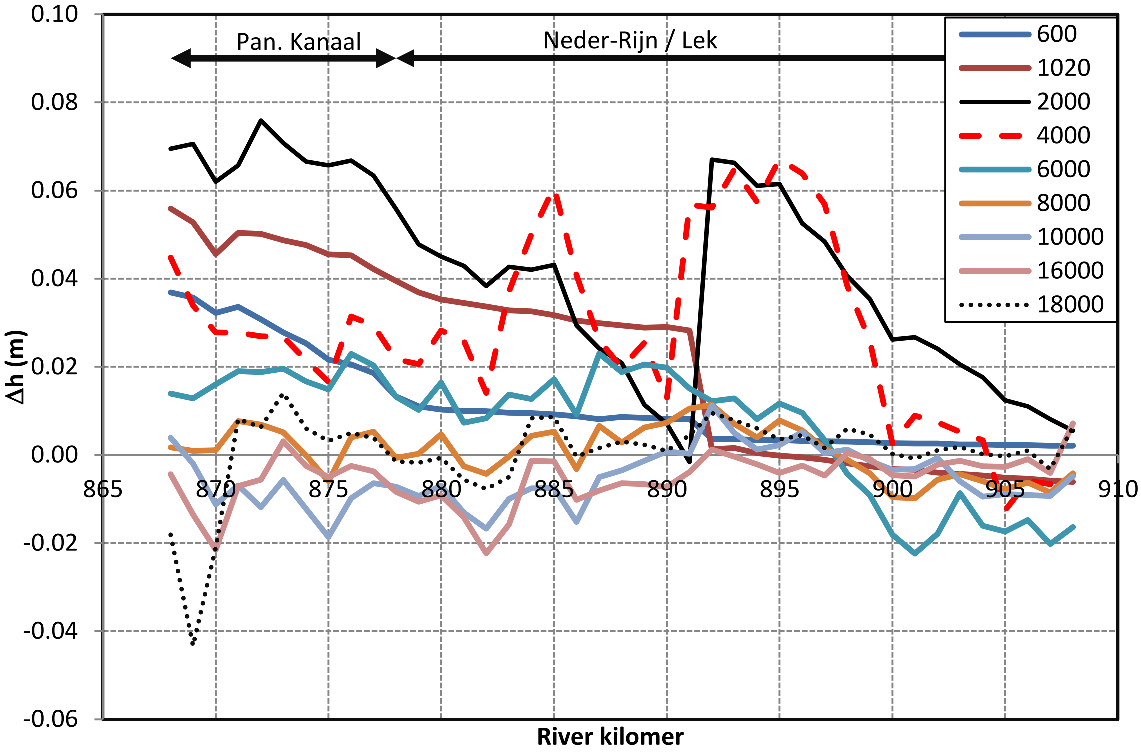


Figure 3.5 Water level differences between Splitsingspunten and Rijntakken model given as (Splitsingspunten-Rijntakken).

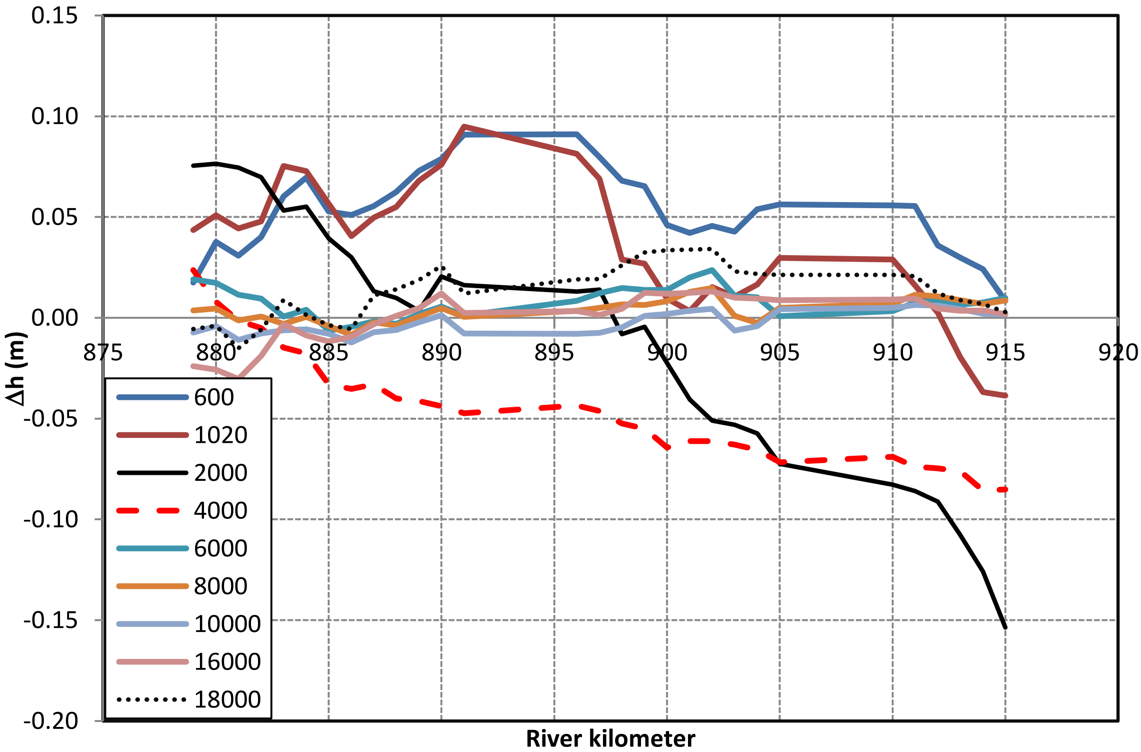


Figure 3.6 Water level differences between Splitsingspunten and Rijntakken model given as (Splitsingspunten-Rijntakken) in the IJssel branch.

The Splitsingspunten model setup and computations have been reviewed and approved by RWS-ON (email of Tijmen Vos, Thu 16-Jan-14 14:41; see Appendix C.1).

3.2 Stationary computations with the Waal model "beno13_5_20m_waal-v1"

With the defined discharge boundary at Pannerdensch Kanaal and chosen time step, we first simulated the 16,000 m^3/s scenario and after having satisfactory result, the simulations for other discharges were carried out. The computations lead to stable results.

Table 3.7 shows the discharge distribution between the Waal and the Pannerdensch Kanaal for all ranges of discharges for the Rijntakken, Splitsingspunten and the Waal model. As expected, the results show very small deviation in the discharge distribution between the Waal and Splitsingspunten model since the boundary at the Pannerdensch Kanaal is determined with Splitsingspunten model and this defines the distribution in the Waal model.

Table 3.7 Discharge distribution in the Rijntakken, Splitsingspunten and Waal model.

Q	Q-Waal			Q-Pannerdensch Kanaal		
	Rijntakken	Splitsingspunten	Waal	Rijntakken	Splitsingspunten	Waal
600	478.57	479.58	479.57	121.44	120.44	120.44
1020	793.48	795.35	795.35	226.53	224.66	224.66
2000	1437.47	1440.94	1441.17	562.53	559.05	558.83
4000	2740.86	2765.03	2765.07	1258.83	1234.95	1234.92
6000	4092.55	4091.89	4092.00	1907.47	1908.12	1908.11
8000	5384.31	5377.80	5377.79	2615.91	2622.09	2622.09
10000	6493.99	6498.63	6498.77	3504.55	3501.20	3501.19
16000	10168.11	10165.85	10164.88	5834.21	5834.62	5834.86
18000	11696.69	11655.01	11654.22	6315.46	6347.94	6344.94

Table 3.6, Figure 3.7 and Figure 3.8 show the differences in water levels at river axis between the Waal, Rijntakken and Splitsingspunten model. From Figure 3.8 one can conclude that the water levels computed with the Waal model are up to a maximum of 1.7 cm different from the ones computed with Splitsingspunten fine grid model. This difference is due to the QH-relation applied at the Splitsingspunten model, which is created based on the computations with Rijntakken coarse grid model. Qh-relation discrepancy propagates further upstream.

Table 3.8 Comparison of the Waal water levels on the river axis with the Rijntakken model.

	600	1020	2000	4000	6000	8000	10000	16000	18000
Average	0.01	0.02	0.03	0.04	0.01	0.00	0.00	0.00	-0.01
Maximum	0.05	0.07	0.08	0.06	0.03	0.02	0.02	0.01	0.00
Minimum	-0.01	-0.01	0.00	0.01	-0.02	-0.03	-0.02	-0.02	-0.02

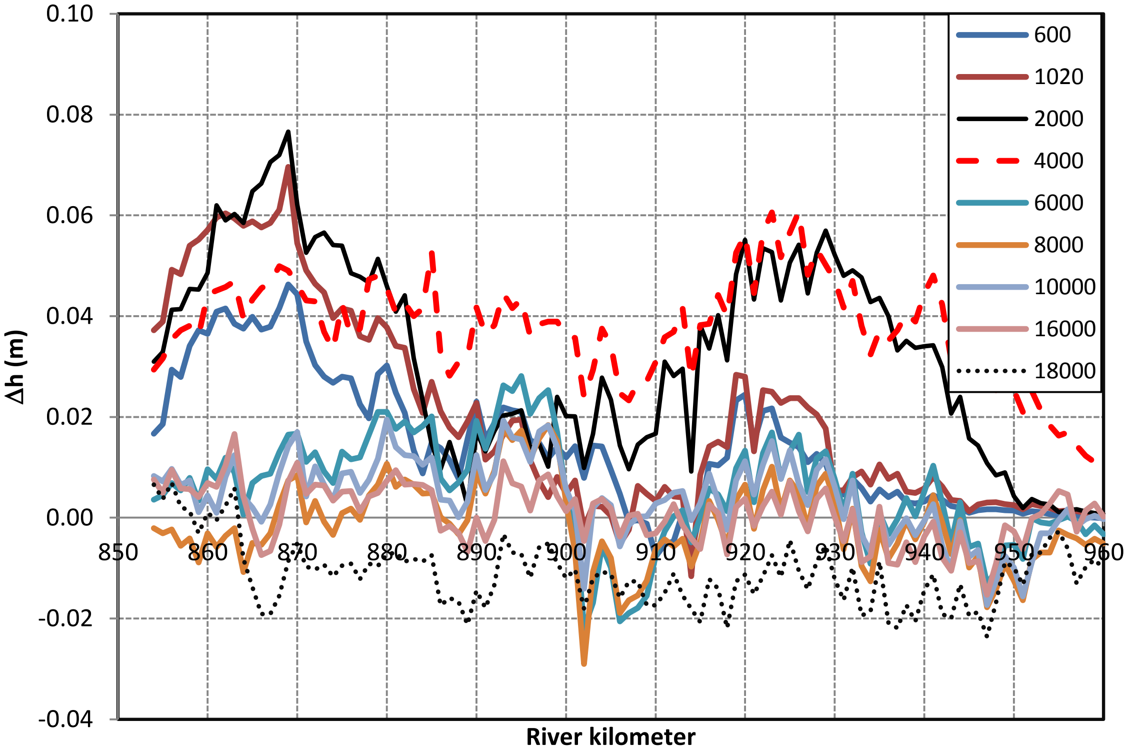


Figure 3.7 Water level differences between the Waal and the Rijntakken model given as (Waal- Rijntakken).

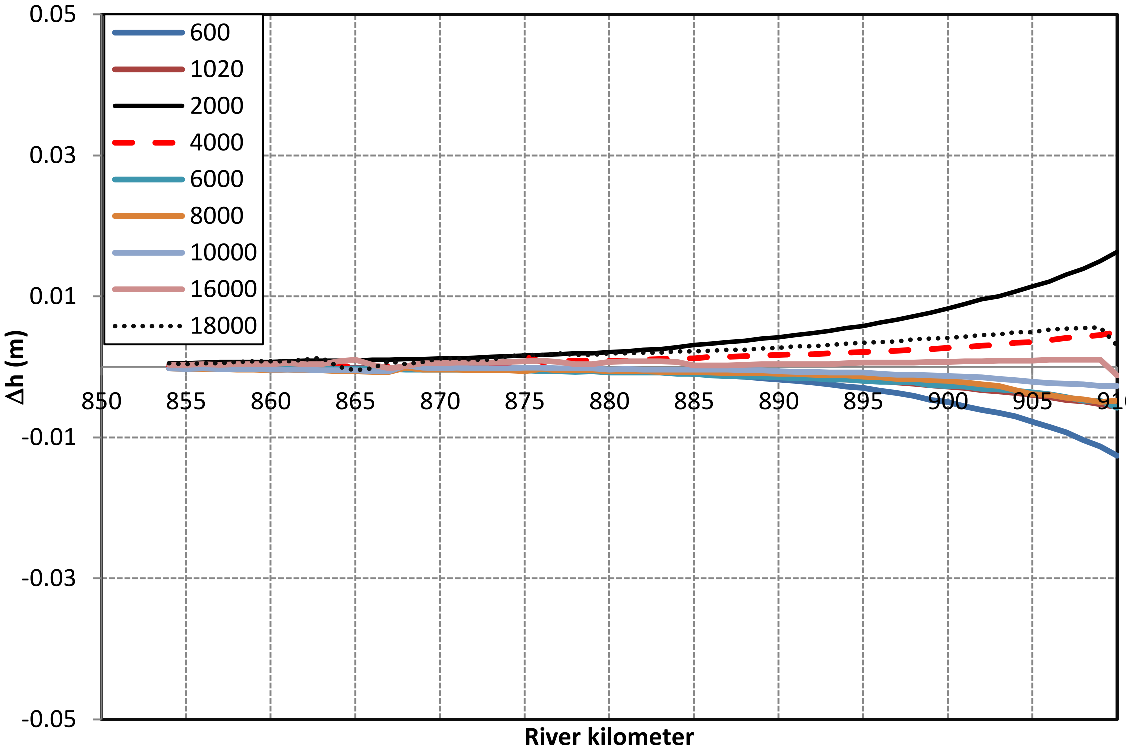


Figure 3.8 Water level differences between the Waal and the Splitsingspunten model given as (Waal-Splitsingspunten).

Computations results are summarised as following:

General observations

- All computations are stable at the end of the 5 days simulations with ThetaC=0.95.
- The measuring point of Pannerdensche Kop falls dry in the 600 m^3/s computation.
- The initial water levels at the “aangetakte plassen” is based on the “maaiveldhoogte” which is much higher than the water level in the main channel during low discharge computations. Meanwhile, there are water bodies located on the floodplains with open connection to the river (“aangetakte plassen”), which do not have a direct connection with the main river in the WAQUA model. Thus, while for these water bodies the current WAQINI procedure might be appropriate, the procedure is not appropriate for the water bodies having the open/wide connection with the main river channel. In the future, it is important to think of some adaptation of WAQINI procedure making a differentiation between two types of “aangetakte plassen”.
- The emptying of the water bodies takes place very slowly.

Discharge Distribution

- For discharges less than 18,000 m^3/s, the discharge distribution between the Waal and the Pannerdensch Kannal in the Waal and the Splitsingspunten model is similar since the boundary at the Pannerdensch Kanaal is determined with the Splitsingspunten model and this defines the distribution in the Waal model. What is interesting is that both the Waal and the Pannerdensch Kanaal receive less discharge in the Waal computation of 18,000 m^3/s compared to the Splitsingspunten model. A small deviation of 3 m^3/s is depicted. This small deviation is acceptable.

Water levels

- For discharges higher than 4,000 m^3/s, the water levels in the Waal model differ from the coarse grid Rijntakken model with less than 5 cm. For other discharges, the differences are higher.
- The differences in water levels between the Waal and the Splitsingspunten model in the overlapping river reach can be explained by the Qh-relation used in the Splitsingspunten model, which is based on the coarse grid Rijntakken model computations. Figure 3.8 shows the influence of this Qh-relation in the Waal model.

The Waal model setup and computations have been reviewed and approved by RWS-ON (email of Tijmen Vos, Monday, January 12, 2015; see Appendix C.2).

3.3 Stationary computations with the Neder-Rijn / Lek model “beno13_5_20m_nrlk-v1”

Initially the 16,000 m^3/s computation was carried out. In this computation, the structures at Neder-Rijn are not operating, but are in full open condition. The position of the structures at bifurcation was initially not fixed to the position obtained from the same discharge computation with Splitsingspunten model. Moreover, the initial model boundary at the Waal was considered at N= 1417. This computation resulted in more discharge going through Pannerdensch Kanaal compared with the Splitsingspunten model. The Waal received less discharge. This is most likely due to presence of a small water body at the boundary location. As a result of these initial computations, Deltares repositioned the boundary location in the Waal some grid cells upstream to the grid line N=1412. This location offered better solution for Neder-Rijn / Lek model.

The last computation result reported in Table 3.9 belongs to the computation with the new Waal boundary location, with fixed position of the structure Hondsbroeksche Pleij. The Regelwerk Pannerden is as well fixed in the last computation to the position corresponding to the same discharge computation with Splitsingspunten model. The discharge distribution complies with the legal distribution better than in the computations with Rijntakken model where the bifurcation structures were not regulated to ensure the desired discharge distribution.

Table 3.9 Discharge distribution in different model computations.

Computation	Q-Waal	Q-Pankanaal	Q-Neder-Rijn	Q-IJssel
Rijntakken	10168.11	5834.21	3375.82	2473.53
Splitsingspunten	10165.52	5834.81	3380.74	2459.17
Neder-Rijn / Lek	10162.79	5836.91	3380.69	2461.60
Neder-Rijn / Lek Fixed Hondsbroeksche Pleij	10162.53	5837.28	3383.28	2459.15
Neder-Rijn / Lek Boundary at Waal N=1412	10165.70	5834.21	3380.69	2459.16

With the fixed position of the bifurcation structures, the computations for other ranges of discharges were carried out, starting with the 600 m^3/s discharge. The first computations showed the following:

- For 600 m^3/s upstream discharge, every computation will results in a new position of the Neder-Rijn / Lek structures, thus, every model run will result in a new stationary solution.
- The end stable position of the structures is different from the sill positions computed with the Splitsingspunten model in 1020 m^3/s discharge computation. The deviation is up to 10 cm for Stuw Driel.

Based on these results, it was decided that for the upstream inflows of less than 4,000 m^3/s, the computation procedure should be different from the procedure applied with previous models. It was decided to carry out the computations with fixed position of the Stuw Driel, which corresponds to the position of the structure in the Splitsingspunten model (during same discharge computation). For getting an insight of this constraint, in this project, the computations are as well carried out even for the situation where the Driel operates according to the regulation rules.

Computation results are compared with the results of the Splitsingspunten and Rijntakken model. Since the previous computations with Rijntakken model were carried out assuming the outflow of 12,5 m^3/s at ARK for discharges at Emmerich less than 2000 m^3/s, two extra computations are carried out without lateral at ARK. In these computations Driel operates according to the regulation rules.

Table 3.10 gives the sill position of all three Neder-Rijn / Lek structures in the computations where Driel is considered at fixed position or operating according to the operation rules. For 2000 m^3/s, the structures end sill position is similar in computations of Splitsingspunten and Neder-Rijn / Lek model (when the structures operate according to the regulation rules). During 1020 m^3/s, the sill position of Stuw Driel is about 10 cm higher than in the Splitsingspunten model and for upstream inflow of 600 m^3/s every computation run will result on to different sill position of structures.

Table 3.10 Computed Driel sill position for low discharges at Neder-Rijn / Lek.

Q	sill position	Driel	Amerongen	Hagestein
600	fixed	5.9763	5.8866	2.8866
	free	varying	varying	varying
1020	fixed	6.7134	5.6841	2.6733
	free	6.8151	5.6916	2.6906
2000	fixed	6.4974	4.7176	1.7445
	free	6.5040	4.7180	1.7390

Table 3.11 gives the discharge distribution in the Neder-Rijn / Lek model for different upstream inflow scenarios. Despite the fact that the Driel sill position is assumed same to the Splitsingspunten model, there is still a slight (negligible) deviation in discharge distribution between the two models for inflows smaller than 4000 m^3/s.

Table 3.11 Discharge distribution between the branches in Rijntakken, Splitsingspunten and Neder-Rijn / Lek model for different range of discharges.

	Model	600	1020	2000	4000	6000	8000	10000	16000	18000
Q-Waal	Rijntakken	479	793	1437	2741	4093	5384	6494	10168	11697
	SPLP	480	795	1441	2765	4092	5378	6499	10166	11653
	Neder-Rijn / Lek	480	795	1446	2760	4092	5378	6499	10166	11653
Q-Pan. Kan.	Rijntakken	121	227	563	1259	1907	2616	3505	5834	6315
	SPLP	120	225	559	1235	1908	2622	3501	5835	6348
	Neder-Rijn / Lek	120	225	554	1240	1908	2622	3501	5835	6348
Q-Neder-Rijn	Rijntakken	2	26	237	729	1098	1541	2109	3376	3434
	SPLP	4	28	246	715	1095	1540	2103	3381	3450
	Neder-Rijn / Lek	6	30	244	719	1095	1540	2104	3381	3453
Q-IJssel	Rijntakken	119	200	327	532	811	1078	1399	2474	2883
	SPLP	116	196	313	522	815	1086	1402	2459	2903
	Neder-Rijn / Lek	115	195	311	522	815	1086	1402	2459	2899

Computations results shown in Table 3.12 and Figure 3.9 to Figure 3.10 can be summarised as following:

General observations

- All computations are stable at the end of the 5 days simulations with ThetaC=0.95.
- The measuring point of Pannerdensche Kop falls dry in the 600 m^3/s computation.
- The initial water levels at the “aangetakte plassen” is based on the “maaiveldhoogte” which is much higher than the water level in the main channel during low discharge computations. Meanwhile, there are water bodies located on the floodplains with open connection to the river (“aangetakte plassen”), which do not have a direct connection with the main river in the WAQUA model. Thus, while for these water bodies the current WAQINI procedure might be appropriate, the procedure is not appropriate for the water bodies having the open/wide connection with the main river channel. In the future, it is important to think of some adaptation of WAQINI procedure making a differentiation between two types of “aangetakte plassen”.
- The emptying of the water bodies takes place very slowly.

Discharge Distribution

- For 600 m^3/s discharge at Emmerich, the inflow to the Neder-Rijn is very small. This makes the model very sensitive to minor changes in the flow conditions. The computations confirm that there is no room for outflows at Amsterdam-Rijnkanaal.
- The operation of the Neder-Rijn / Lek structures with its current implementation, for low discharge condition of 600 m^3/s, yields multiple solutions. This is due to the sensitivity of the structure to very small changes in water levels. Accordingly, for computations with discharges lower than 4000 m^3/s we fixed the Stuw Driel to the sill position computed with Splitsingpunten model for same discharge condition.
- We recommend to test and adjust the operation rules of the structures at the Neder-Rijn / Lek for stationary conditions.

Water levels

- For discharges higher than 8,000 m^3/s, the water levels in the Neder-Rijn / Lek model differ from the coarse grid Rijntakken model in less than 5 cm. For other discharge ranges, the differences are higher than 5 cm.

- The differences in water levels between the Neder-Rijn and Splitsingspunten model in the overlapping river reach is justified by the Qh-relation defined in the Splitsingspunten model based on the coarse grid computations. Figure 3.10 shows the influence of this Qh boundary in the Splitsingspunten model can be up to 8 cm.

Table 3.12 Comparison of the Neder-Rijn / Lek water levels on the river axis with Rijntakken model.

	600	1020	2000	4000	6000	8000	10000	16000	18000
Average	0.00	0.01	0.02	0.02	0.03	0.01	0.00	0.00	0.02
Maximum	0.03	0.05	0.07	0.08	0.09	0.06	0.03	0.01	0.03
Minimum	-0.01	-0.01	-0.01	0.00	0.00	0.00	-0.02	-0.02	0.00

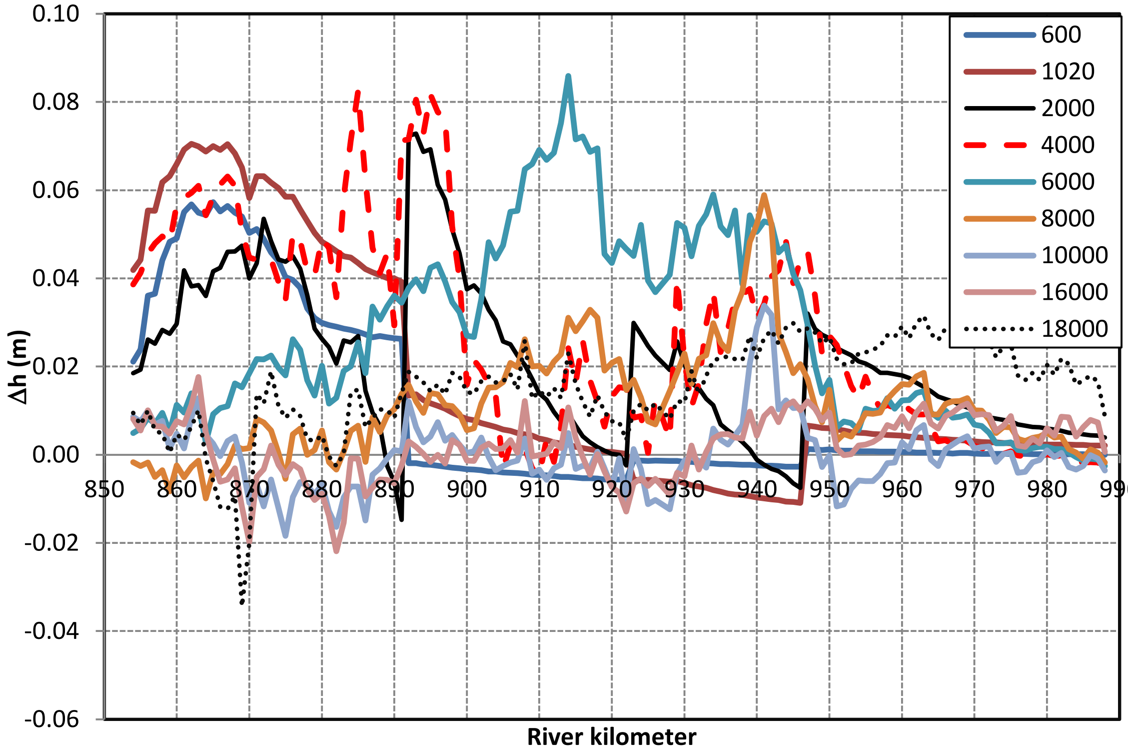


Figure 3.9 Water level differences between the Neder-Rijn / Lek and Rijntakken model given as (Neder-Rijn / Lek-Rijntakken).

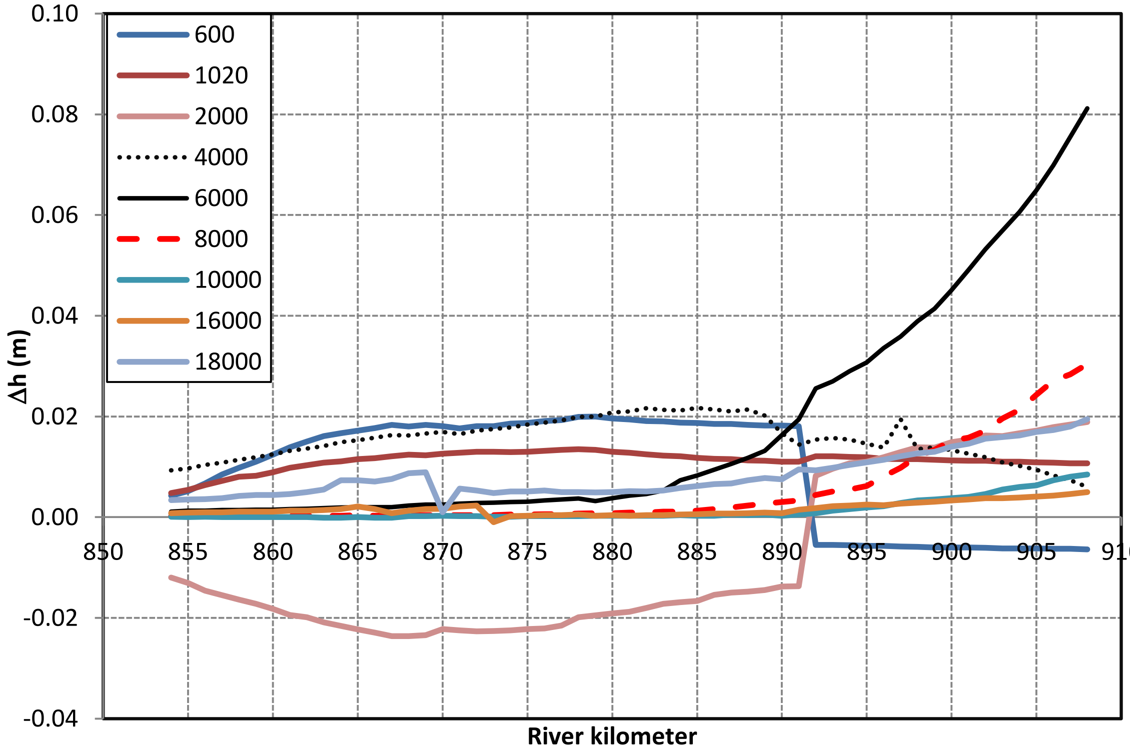


Figure 3.10 Water level differences between the Neder-Rijn / Lek and Splitsingspunten model given as (Neder-Rijn / Lek-Splitsingspunten).

The Neder-Rijn / Lek model setup and computations have been reviewed and approved by RWS-ON (email of Tijmen Vos, Thursday, August 07, 2014 6:46 PM; see Appendix C.3).

3.4 Stationary computations with the IJssel model “beno13_5_20m_ijssel-v1”

Initially the computation for the 16,000 m^3/s at Emmerich was carried out. In this computation, the structures at bifurcation are not operating, but are in fixed position defined with the Splitsingspunten model computations. The model boundary at the Waal is as for the Neder-Rijn / Lek model at N=1412. Computation results are compared with Rijntakken and Splitsingspunten model. Water levels differences are in order of less than 5 cm for the MHW discharge. Afterwards the computations for the other ranges of discharges were carried out. The computation results are presented in Table 3.13 to Table 3.14 and Figure 3.11 to Figure 3.12.

Table 3.13 Discharge distribution between the branches in Rijntakken, Splitsingspunten and IJssel model for different range of discharges.

	Model	600	1020	2000	4000	6000	8000	10000	16000	18000
Q-Waal	Rijntakken	479	793	1437	2741	4093	5384	6494	10168	11697
	SPLP	480	795	1441	2765	4092	5378	6499	10166	11653
	IJssel	480	795	1441	2760	4092	5378	6499	10165	11652
Q-Pankan.	Rijntakken	121	227	563	1259	1907	2616	3505	5834	6315
	SPLP	120	225	559	1235	1908	2622	3501	5835	6348
	IJssel	120	225	559	1240	1908	2622	3501	5834	6346
Q-Neder-Rijn	Rijntakken	2	26	237	729	1098	1541	2109	3376	3434
	SPLP	4	28	246	715	1095	1540	2103	3381	3450
	IJssel	4	28	246	703	1095	1540	2103	3380	3452
Q-Yssel	Rijntakken	119	200	327	532	811	1078	1399	2474	2883
	SPLP	116	196	313	522	815	1086	1402	2459	2903
	IJssel	116	197	314	538	815	1086	1402	2459	2901

Table 3.14 Comparison of the IJssel water levels on the river axis between the IJssel and Rijntakken model.

	600	1020	2000	4000	6000	8000	10000	16000	18000
Average	0.05	0.07	0.06	0.05	0.00	0.00	0.00	0.00	0.01
Maximum	0.11	0.17	0.16	0.11	0.05	0.04	0.04	0.03	0.05
Minimum	0.00	0.00	-0.01	0.01	-0.03	-0.03	-0.03	-0.03	-0.02

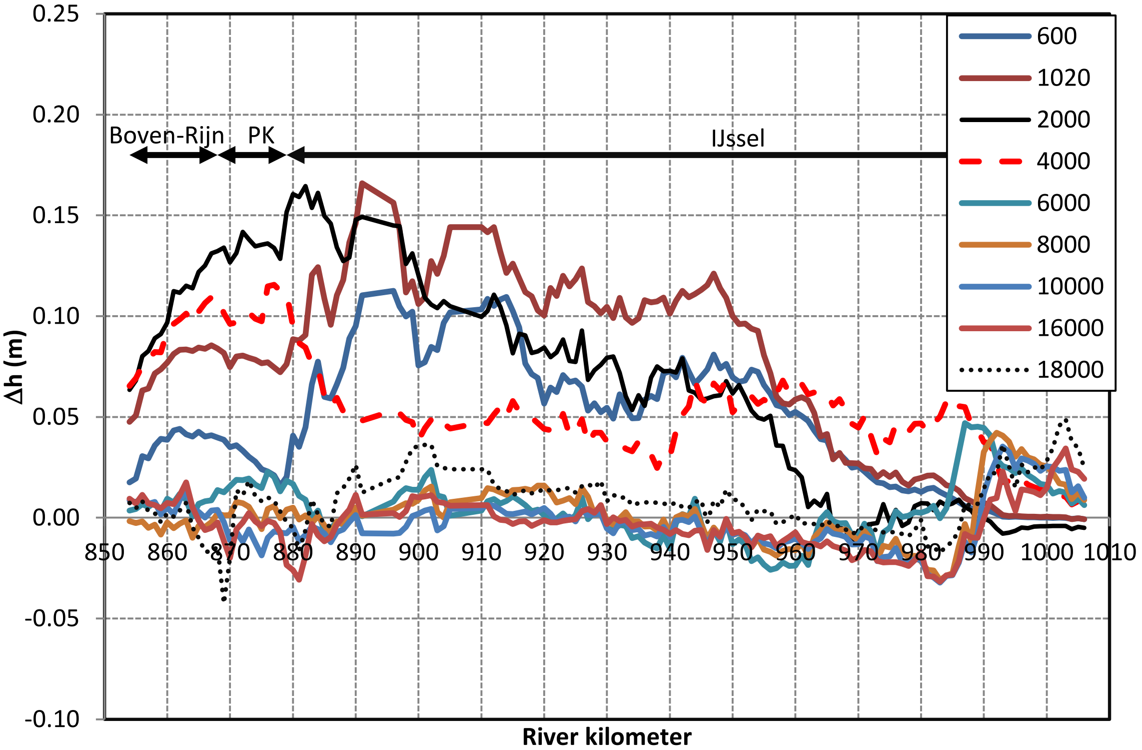


Figure 3.11 Water level differences between the IJssel and Rijntakken model given as (IJssel- Rijntakken).

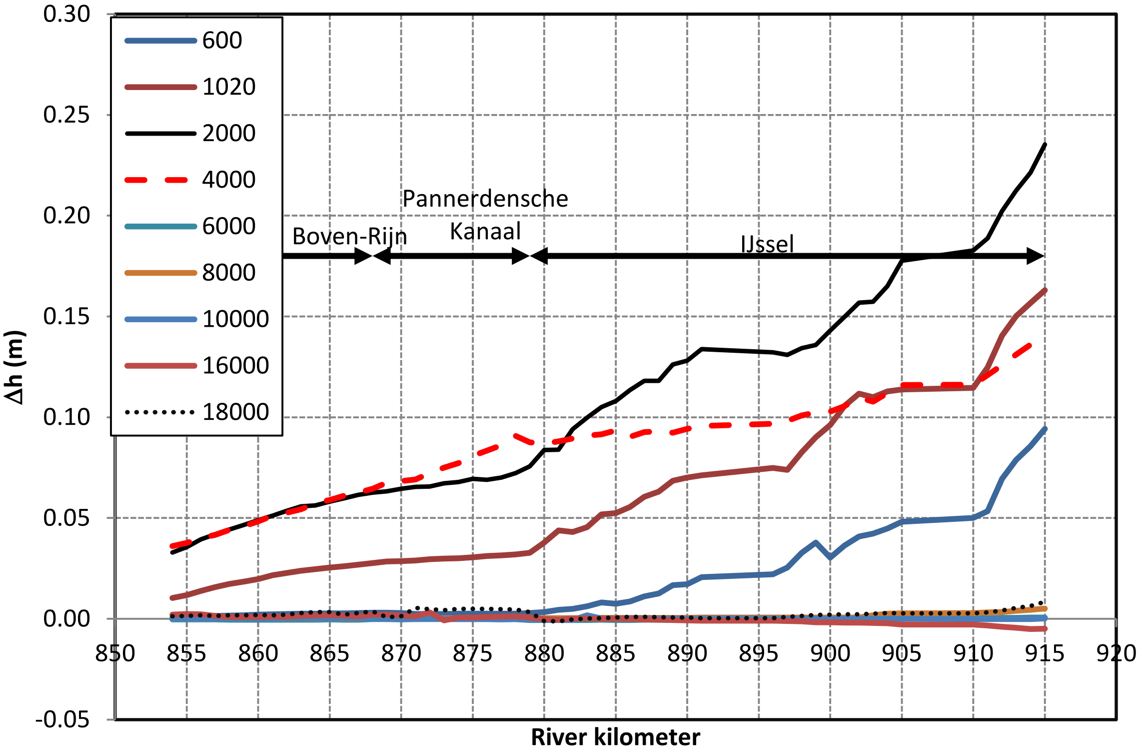


Figure 3.12 Water level differences between the IJssel and Splitsingspunten model given as (IJssel- Splitsingspunten).

Computations results can be summarised on the following:

General observations

- All computations are stable at the end of the 5 days simulations with ThetaC=0.95.
- The measuring point of Pannerdensche Kop falls dry in the 600 m^3/s computation.
- The initial water levels at the “aangetakte plassen” is based on the “maaiveldhoogte” which is much higher than the water level in the main channel during low discharge computations. Meanwhile, there are water bodies located on the floodplains with open connection to the river (“aangetakte plassen”), which do not have a direct connection with the main river in the WAQUA model. Thus, while for these water bodies the current WAQINI procedure might be appropriate, the procedure is not appropriate for the water bodies having the open/wide connection with the main river channel. In the future, it is important to think of some adaptation of WAQINI procedure making a differentiation between two types of “aangetakte plassen”.
- The emptying of the water bodies takes place very slowly.

Discharge Distribution

- Discharge distribution among Rhine branches in the IJssel and Splitsingspunten model is similar for all ranges of discharges except for 4000 m^3/s. During this discharge computation, some 5 m^3/s discharge extra enters to Pannerdensch Kanaal, while some 16 m^3/s extra goes to IJssel compared with the Splitsingspunten model. The Neder-Rijn branch does not withdraw the defined discharge. This discharge distribution should be corrected in the future models.

Water levels

- For discharge levels higher than 4,000 m^3/s, the water levels in the IJssel model differ from the Rijntakken model in less than 5 cm.
- Water levels in the IJssel model are in general higher than in the Rijntakken model despite the higher discharges computed in the latter.
- The differences in water levels between the IJssel and Splitsingspunten model in the overlapping river reach are very small for discharges of higher than 4000 m^3/s, but are significantly different for the lower discharges despite the fact that there are no discharge differences between the models for discharges of less than 4000 m^3/s. For same flow discharge, higher water levels are computed in the IJssel model. This is justified by the Qh-relation defined in the Splitsingspunten model. Figure 3.12 shows the influence of this Qh boundary in the IJssel model.

The IJssel model and computations are reviewed and approved by RWS-ON (email of Tijmen Vos, Thursday, Monday, August 11, 2014 1:10 PM; see 5C.4).

3.5 Applicability of subdomain models

The branch models can be used for computing the hydraulic effect of the interventions keeping into account the general modelling rules, such as the distance of the intervention area with regard to the model boundaries. To evaluate the influence of the intervention in discharge distribution among the Rhine branches one should use the Splitsingspunten model. The other models are not suitable for this purpose. The discharge distribution is predefined and fixed in the branch models. Accordingly, in case there is an expected effect on discharge distribution from a measure that would be located in one of the branch models, additional analysis using the entire Rijntakken model will be required. Such an effect may be observed in the branch model as an effect on water level near the bifurcation.

We note that no recalibration of the refined models was carried out. Nevertheless, the results of the refined models compare well with the calibrated model as demonstrated in the comparisons. Still, the refined sub-models can be used to assess the effect of the measure in the relative terms rather than in absolute terms. Thus, water level differences rather than absolute water levels should be used for analysis.

The models are tested for a range of discharges from 600 m^3/s to 18,000 m^3/s. The rating curves applied at the boundaries of Splitsingspunten model are valid for the same discharge range. If the discharge distribution between branches differs significantly; the extrapolation in Qh-relation is possible. Thus, it is advised to adjust the Qh-relation for two additional discharges: one lower than 600 m^3/s and a second higher than 18,000 m^3/s.

For discharges less than 4,000 m^3/s at Emmerich, the Stuw at Driel is in a fixed position in the Neder-Rijn / Lek model. The structures Regelwerk Pannerden and the Hondsbroeksche Pleij have a fixed position in the Splitsingspunten and other branch models. These conditions should be taken onto account when carrying out computations with the subdomain models.

4 Conclusions and recommendations

4.1 Summary and Conclusions

Within this project 4 subdomain models are created for the Rhine River in the Netherlands. The models are created for each of the Rhine branches and the bifurcation (Splitsingspunten) area. The models are tested for stationary discharges for as low as 600 m^3/s to as high as 18,000 m^3/s. Shall the models be used for other discharge ranges, then it is necessary to update the hydraulic conditions at the boundaries, the initial fields, the sill positions of the Neder-Rijn / Lek structures, and the conditions applied for the bifurcation structures.

The subdomain models fulfil the requirements defined at the start of the project. For all models (except the Neder-Rijn / Lek model), the water levels on the river axis in the subdomain models differ in less than 5 cm compared to the Rijntakken coarse grid model for upstream inflows of 6,000 m^3/s or higher. The Neder-Rijn / Lek model still records higher water levels for upstream inflow of 6,000 m^3/s due to schematisation projection differences between the fine and coarse grid. All the model computations are stable at the end of computations during different discharge scenarios. The water levels in the fine model are, in general, higher than the water levels in the coarse grid Rijntakken model.

In this project, we devised an approach to create the subdomain models in the future. This approach is presented and discussed in Chapter 2.

This task has led to important insights into the operation of the structures at bifurcation and the influence of the weir at Driel on the bifurcation point at the IJsselkop. The project has made a significant contribution to our knowledge with regard to the use and development of the models and especially for the model calibrations in the future.

The created models can be used for assessing the impact of interventions along the river within the framework of the permission grants. Due to the low flows at the Neder-Rijn / Lek for the upstream discharge of 600 m^3/s at Emmerich, it is not recommended to use this model for assessing the hydraulic effect of the measures for such low discharge condition. For discharges less than 4000 m^3/s at Emmerich, the Stuw at Driel is in a fixed position in the Neder-Rijn / Lek model. This should be taken into account when carrying out computations with this model. Due to the predefined discharge distribution in the branch models, they cannot be used to assess the effect of the intervention in the discharge distribution. The Splitsingspunten model can be used for this purpose.

4.2 Recommendations

We recommend using the fine models in analysis of the hydraulic effect of the interventions along the Rhine river; as the subdomain models are finer and allow for more detailed schematisation of the measures.

When the effect of measures affects the discharge distribution, we don’t recommend using the branch models. In this case, we recommend using the Splitsingspunten model. Shall the interventions extend outside the Splitsingpunten model area, we recommend using the entire Rijntakken model.

At the beginning of the project, we made one attempt to create a fine grid Rijntakken model (for the entire Rijntakken). Due to software limitations and the complexity of analysing the computation results for such a large model, this choice proved to be problematic. In the future, and when such an option is feasible, it is recommended to obtain the Qh-relation for the Splitsingspunten model out of the Rijntakken fine grid model.

It has been assumed that no recalibration is necessary for the fine grid models. However, the impact of the grid refining on the calibration results has not been tested. It is recommended to investigate this assumption in the future.

The fine grid models are tested for the same range of discharges for which the Qh-relation is valid. It is recommended to extend the Qh-relation for upstream discharge levels lower than 600 m^3/s and higher than 18,000 m^3/s.

In this project, the sill position of the Regelwerk Pannerden is regulated to ensure the legal discharge distribution during 16,000 m^3/s at Emmerich. For this condition, the Hondsbroeksche Pleij was not closed. We may need to reconsider which operation rules for the bifurcation structures should be used in future:

- Fix Regelwerk Pannerden to the position which ensures the legal discharge distribution while the Hondsbroeksche Pleij is then not fully closed but operating; or
- Allow a small deviation from the legal discharge distribution and fulfill to the condition that the Hondsbroeksche Pleij does not operate for discharges equal or lower than 16,000 m^3/s.

We recommend to test and adjust the operation rules of the structures at the Neder-Rijn / Lek for stationary conditions. With the current operation rules, it is not possible to reach unique stationary solution in the Neder-Rijn / Lek model for flow conditions with operating structures.

Reaching stable water levels in the water bodies for discharges less than or equal to 10,000 m^3/s takes a lot of computational time. It is recommended to improve Baseline schematisation of the water bodies (“plassen”) which are either having inappropriate information or are not at all considered as such in Baseline schematisation.

Changes in the WAQINI tool are recommended in order to cope with different types of water bodies, depending on their connection and proximity to the river.

5 Literature

Agtersloot, R.C. 2012, Implementatie stuwprogramma 2005/2006 Neder-Rijn / Lek in WAQUA. P0040.9

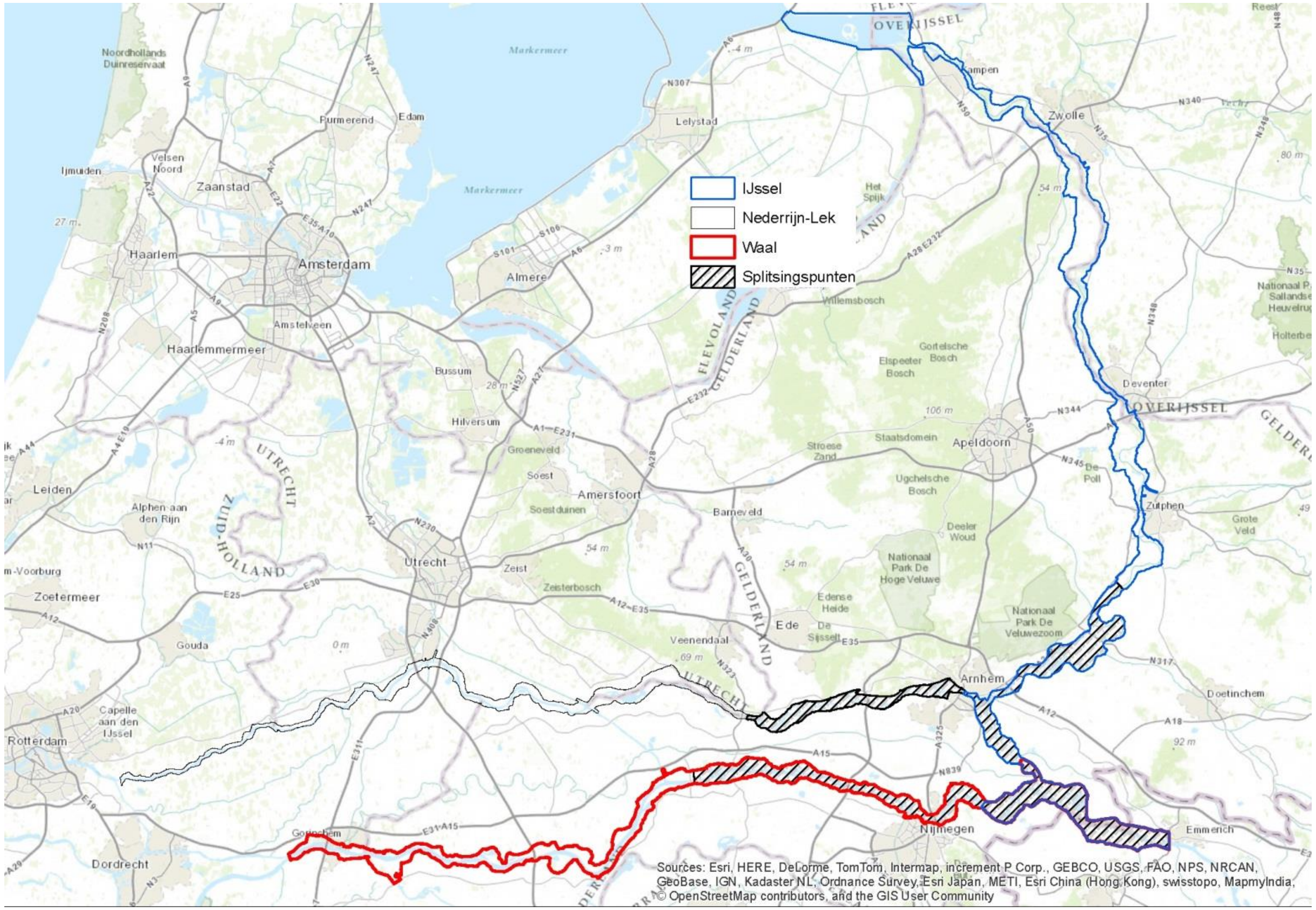
Beijer, D. 2012, Afleiding stationaire lateralen Rijntakken. RWS-ON. Memo of 9 July 2012

Driessen, T.L.A., van der Sande, B., 2013 Baseline en WAQUA schematisaties Rijntakken2013. RHDHV Definitief rapport BC3784-101-100

de Goede, E.D., van Kester, J., 2013. Toepasbaarheid van kleine roostercellen in WAQUA voor overlaten. 1207880-006-ZWS-0009

Riza. 2005, Baseline Technische Documentatie Baswaq 1.41. RIZA-Werkdocument 2005.112

A Extent of the subdomain models



B Stationary laterals for different discharge conditions at Emmerich (Beyer, 2012)

Laterale toestroming	Locatie	2000 m^3/s	3000 m^3/s	4000 m^3/s	6000 m^3/s	8000 m^3/s	10000 m^3/s	12000 m^3/s	15000 m^3/s
Hollands_Duits_gemaal_Nijmegen	883.00_WA	1.19	1.79	2.38	3.58	5.73	7.59	8.49	9.98
Land_van_Altena	958.00_WA	0.78	1.17	1.57	2.35	3.38	5.09	5.70	6.55
gemaal_Kandia	874.00_PK	0.81	1.22	1.62	2.43	3.32	4.04	4.44	5.13
Arnhem_ca	883.00_NR	0.21	0.31	0.41	0.62	0.81	0.97	1.08	1.24
Heelsumsche_Beek_ca	896.00_NR	1.32	1.98	2.64	3.96	5.25	7.91	8.79	10.13
GJH_Kuykgemaal_(ontlasting_Linge)	902.00_NR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gemaal_HA_van_Beuningen_(ontlasting_Linge)	929.00_NR	-11.19	-10.53	-9.88	-8.56	-3.60	1.13	1.88	2.64
Lopikerwaard	965.00_LEK	0.57	0.86	1.15	1.72	2.22	3.52	4.60	5.22
Bergambacht_en_de_Overwaard	986.00_LEK	1.35	2.02	2.69	4.04	4.16	5.29	6.55	7.47
Rozendaalsche_en_Beekhuizerbeek	886.00_IJ	0.17	0.25	0.33	0.50	0.66	0.78	0.87	1.01
Liemers_en_Bevermeer	900.00_IJ	1.33	2.00	2.66	4.00	5.17	6.26	6.91	7.91
Oude_IJssel	901.00_IJ	10.52	15.79	21.05	31.57	41.91	48.77	54.29	62.67
Leuvenheimsche_Soerensche_en_Groote_Beek	916.00_IJ	1.09	1.64	2.18	3.28	4.63	5.88	6.70	7.65
diverse_beken_gemalen_km_920_930	922.00_IJ	2.80	4.20	5.60	8.40	11.00	13.52	15.50	16.46
Twentekanaal_diverse_beken	931.00_IJ	9.25	13.88	18.50	27.75	33.39	40.86	47.68	52.53
diverse_beken_en_gemalen_km_930_940	935.00_IJ	1.12	1.68	2.23	3.35	4.14	5.01	5.86	6.40
diverse_beken_en_gemalen_km_944_957	946.00_IJ	1.45	2.17	2.89	4.34	5.72	7.23	8.47	9.46
diverse_beken_en_gemalen_km_975_985	977.00_IJ	3.28	4.93	6.57	9.85	11.10	13.32	15.73	17.67
diverse_gemalen_km_987_1002	992.00_IJ	0.16	0.24	0.33	0.49	0.99	1.51	1.92	2.15
Schipbeek	942.00_IJ	2.74	4.12	5.49	8.23	10.01	12.06	14.01	15.74

C RWS-ON acceptance of the models

C.1 Splitsingspunten model

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Thursday, January 16, 2014 2:41 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL)
Subject: Resultaten deelmodellen

Migena,

We hebben gekeken naar de derde versie van het Splitsingspunten-model inclusief alle afvoerniveau‘s. Hieronder de opmerkingen. De algemene opmerkingen gelden eigenlijk ook voor de andere deelmodellen, en zouden ook in beno13_5 zelf moeten (dus met het 40m-rooster). Als het daar ook al in aangepast kan worden, zou dat mooi zijn. Verder hebben we geprobeerd te kijken naar de MHW-som van het IJssel-deelmodel en hebben we met Martin gebeld over de aanpassing van de sectiebestanden.

Opmerkingen splitsingspuntenmodel v3

- Algemeen: alle siminp’s: checkpoints: vsections: check-sectu-ontrekkingsranden staat nog aan, verwijderen in definitief model, ook definitie punten en lijnen hiervan uit de siminp’s halen.
- Algemeen: naam afvoerraai op benedenrand Waal, Neder-Rijn en IJssel klopt niet (is niet Werkendam, Krimpen, Ketelmeer), wijzigen in modelrand + km-raai.
- Algemeen: randvoorwaarden: commentaar in qh-randvoorwaarde Lek + IJssel klopt niet, hoge afvoeren Lobith ontbreekt een 0.
- Algemeen: randvoorwaarden: commentaar voor alle drie de qh-randen aanpassen:

- huidige tekst eruit (klopt niet voor dit model);
- toevoegen dat dit qh-randen zijn die zijn afgeleid voor het splitsingspuntenmodel op basis van beno13_5 met 40 m rooster, juiste lokatie (km + N-lijn noemen).

- Algemeen: naam regelwerk Hondsbroeksche Pleij is niet zichtbaar in Waqview => in bestand kunstwerk-p_handm moet een naam komen vergelijkbaar met de naam in kunstwerk-l (...., name='Regelwerk Hpleij 01 ').
- Algemeen: Q-raaien km 896, 897, 905 en 910 (alle IJssel) moeten eruit, zijn niet realistisch => uitschakelen usections in siminp.
- Algemeen: verwijderen check-sectu-ontrekkingsranden uit vsections.
- Algemeen: Q-raaien hw-meting eruit, zijn niet nodig voor beno.
- Algemeen: Q-raaien knip (voor de calibratie) eruit, zijn niet nodig voor beno.
- Algemeen: Q-raai 879 Neder-Rijn + 879 IJssel zijn te lang (beide over volledige breedte) => handmatig aanpassen, voorstel: beide raaien op N = 1543, deel Neder-Rijn tot aan M = 654, deel IJssel vanaf M = 654.
- Algemeen: Q-raai 880 Neder-Rijn is te lang, handmatig aanpassen, stoppen op M = 617.
- Algemeen: Q-raai 868 Pannerdensch kanaal is te lang, handmatig aanpassen, starten op M = 592.
- Algemeen: Q-raai 869 Pannerdensch kanaal is te lang, handmatig aanpassen, starten op M = 611.

- Algemeen: Q-raai Nijmegenhaven is te lang, moet gelijk zijn aan Q-raai 885 (start op M = 220).
- Algemeen: toevoegen Q-raai HwgeulLent N = 1741, M start = 242, M eind = 263.
- Algemeen: toevoegen Q-raai HwgeulVeessen (lokatie zelf even uitzoeken, ergens midden in geul leggen).
- Afvoer 600 m3/s: model zeer stabiel, mooi.
- Afvoer 1020 m3/s model zeer stabiel, mooi.
- Afvoer 2000 m3/s model zeer stabiel, mooi.
- Afvoer 4000 m3/s model zeer stabiel, mooi.
- Afvoer 6000 m3/s model zeer stabiel, mooi.
- Afvoer 8000 m3/s model zeer stabiel, mooi.
- Afvoer 10000 m3/s model zeer stabiel, mooi.
- Alle afvoeren: regelwerk Pannerden moet niet actief sturen. Instelling overnemen uit 16.000 m3/s som en vast opnemen in sininp's voor 600 t/m 16.000 m3/s, instelling uit 18.000 m3/s som overnemen en vast opnemen in sininp voor 18.000 m3/s. Sturingstabel graag opnemen in een apart bestand. **Martin, kun jij dit bevestigen.**
- Afvoer 16000 m3/s:

- model zeer stabiel, mooi;
- voor het definitieve splitsingspuntenmodel willen we voorstellen dat Hpleij niet beweegt. Reden is dat het model gebruikt gaat worden om veranderingen in de afvoerverdeling te bepalen ten gevolge van een gewenste ingreep. Een vaste instelling kan op twee manieren: volledig dicht of overnemen uit dit model. Volledig dicht lijkt beter want is conform het beleid (om pas bij afvoeren boven 16.000 m3/s Lobith de Neder-Rijn / Lek te ontzien). Dan accepteren we dus een kleine afwijking in de afvoerverdeling NR-IJ. **Martin, kun jij dit bevestigen.**

- Afvoer 18.000 m3/s:

- model redelijk stabiel;
- voor het definitieve splitsingspuntenmodel willen we voorstellen dat Hpleij niet beweegt. Reden is dat het model gebruikt gaat worden om veranderingen in de afvoerverdeling te bepalen ten gevolge van een gewenste ingreep. Ons voorstel is de instelling over te nemen uit dit model. **Martin, kun jij dit bevestigen.**

<u>Opmerkingen deelmodel IJssel</u>

- afvoer 16.000 m3/s: zoals net besproken kan de SDS-file niet worden ingelezen. Afgesproken is dat we een poging gaan doen met een kleiner bestand: alle overbodige raaien eruit (zie opmerkingen splitsingspuntenmodel) en history inkorten tot de laatste 100 minuten. Daarna kijken we of de SDS geopend kan worden.

<u>Aanpassen sectiebestand beno13_5 en j95_5</u>

- We hebben dit met Martin kortgesloten. De sectiebestanden voor beide schematisaties kunnen worden verbeterd. Wij zullen voor beide een shapefile aanleveren, die jullie dan moeten opnemen in de geodatabase van de betreffende schematisatie. De aanlevering hiervan kunnen wij doen op 27 januari. Zoals besproken betekent dit het opnieuw vullen van de deelmodellen met Baseline. Daarvoor gebruiken we dan gelijk de Baseline versie die RWS ook (gaat) gebruiken. Afgesproken is dat jij nog even met Martin kortsluit welke Baseline versie dat precies is.

Met vriendelijke groet,

Tijmen
Dénes

C.2 Waal model

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Thursday, August 07, 2014 6:46 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL)
Subject: RE: other discharges Waal

Migena,

We hebben naar de overige afvoeren voor de Waal gekeken. Onze conclusies staan hieronder, per afvoerniveau. Over het algemeen zien de modellen er zeer goed uit qua stabiliteit, complimenten! We gaan akkoord met de modellen.

600 m3/s Lobith
- Zeer stabiel.
- Wat opvalt is dat meetpunt Pannerdensche Kop droogvalt. Hier moeten we in j15_5 naar kijken, nu niets aan te doen.
- De initiële waterstanden in aangetakte plassen passen niet bij hele lage afvoeren. Oplossing vergt een aanpassing van Waqini, nu niets aan te doen. We hebben hier wel een idee dat we nog als wens voor KPP2015 zullen opsturen.
- Het leeglopen van aangetakte plassen is nog lang niet voltooid. Dit gaat erg langzaam, maar dit ligt voor een deel ook aan de schematisatie. Nu niets aan te doen.

1020 m3/s Lobith
- Zeer stabiel.

2000 m3/s Lobith
- Zeer stabiel, op twee waterstandslokaties na. Kleine slingering in afvoer, max 1 m3/s, geen probleem. Nog geen oorzaak gevonden.

4000 m3/s Lobith
- Zeer stabiel, op één q-raai na (km-raai 910, slingering max 1,5 m3/s, oorzaak is schematisatiefout, geen probleem.

6000 m3/s Lobith
- Zeer stabiel, op één q-raai na (km-raai 900, slingering max 2 m3/s, oorzaak nog niet bekend, geen probleem.

8000 m3/s Lobith
- Behoorlijk stabiel, op diverse q-raaien rond km-raai 921 na, slingering max 2 m3/s, oorzaak nog niet bekend, geen probleem.

10.000 m3/s Lobith
- Behoorlijk stabiel, op diverse q-raaien rond km-raai 905 en 959 na, slingering max 10 m3/s, oorzaak nog niet bekend, acceptabel.

18.000 m3/s Lobith
- Redelijk stabiel, in het splitsingspuntengebied slingeringen in waterstand en afvoer, tot max 4 mm en 35 m3/s, oorzaak waarschijnlijk dicht regelwerk Pannerden.
- We twijfelen of de keus voor afregelen afvoerverdeling bij 18.000 m3/s met behulp van het regelwerk Pannerden de juiste is. Moet eigenlijk met rivierverruiming gepaard gaan, anders lukt het niet de gewenste afvoer richting de Waal te krijgen.
- Hier kan nu niets aan gedaan worden, **als we de deelmodellen opnieuw maken willen we hier beter over nadenken en dit bespreken**. Een mogelijkheid is om in de drie takmodellen de gewenste afvoerverdeling op te leggen als onttrekking, in combinatie met een vaste instelling van de regelwerken. Het splistsingspuntenmodel wijkt dan af, maar dan zijn er tenminste modellen van elke tak met de gewenste afvoer.

Met vriendelijke groet,

Dénes
Tijmen

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Thursday, December 12, 2013 7:26 PM
To: Migena Zagonjolli
Cc: Scholten, Martin (WVL); Beyer, Dénes (ON)
Subject: RE: splitsingspunt WAQUA model

Migena,
…

We hebben naar het deelmodel voor de Waal gekeken. Opmerkingen:
- Er is nu een ruwheidsbestand zomerbed apart voor de Waal gemaakt. Dit vinden we niet handig. Waarom opknippen? Liever het totale bestand voor de hele Rijntakken toepassen.
- Om overbodige meldingen in de waqpre-m te voorkomen, graag de BAR_TABLE uitcommentarieren.
- Afvoerraai Q-Tiel-meting is te kort.
- Model is zeer stabiel, mooi!
- Stroombeeld ziet er goed uit, mooi!

…

Mvg,

Dénes
Tijmen

C.3 Neder-Rijn / Lek model

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Monday, January 12, 2015 5:13 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL); Aukje Spruyt
Subject: RE: Neder-Rijn / Lek final model results

Migena,

We hebben de gemaakte berekeningen bekeken. Onze bevindingen staan hieronder. Over het algemeen zien de modellen er zeer goed uit qua stabiliteit, complimenten! We gaan akkoord met de modellen. Er is nog één aandachtspunt (zie algemeen). Voor de afvoeren 1020 en 2000 m3/s Lobith kiezen we ervoor Driel vast te zetten. Reden is uniformiteit voor alle afvoeren waarbij stuw Driel in bedrijf is. Ook voor deze deelmodellen geldt dat we de SIMINP's nog willen aanvullen.

Algemeen
- Q-raaien hw-meting eruit, zijn niet nodig voor beno. Zijn nog opgenomen in sommige siminp's, graag verwijderen.

1020 m3/s Lobith 5 dagen Driel vast
- Waterstanden benedenstrooms Hagestein zijn nagenoeg stabiel (hele lichte stijging, verwaarloosbaar), alleen slingeringen rondom stuw Hagestein (0.5 mm).
- Waterstanden tussen Amerongen en Hagestein zijn nagenoeg stabiel (hele lichte stijging, verwaarloosbaar), met uitzondering van Hagestein boven en de twee km-raaien bovenstrooms van stuw Hagestein. Hagestein boven slingert ca 0.8 mm.
- Waterstanden tussen Driel en Amerongen zijn nagenoeg stabiel (hele lichte stijging, verwaarloosbaar).
- Waterstanden bovenstrooms Driel zijn stabiel. IJsselkop slingert ca 1 mm.
- Meetpunt IJsselkop geeft geen goed resultaat want worden beïnvloed door de onbepaalde tak. Meetpunt Looveer valt droog.
- De afvoer door de Neder-Rijn wijkt iets af van de beoogde afvoer maar is wel behoorlijk stabiel. Sommige raaien nabij de stuwen slingeren, maximaal 1.2 m3/s.

2000 m3/s Lobith 5 dagen Driel vast
- Waterstanden benedenstrooms Hagestein zijn stabiel.
- Waterstanden tussen Amerongen en Hagestein zijn stabiel.
- Waterstanden tussen Driel en Amerongen zijn stabiel.
- Waterstanden bovenstrooms Driel zijn stabiel. Meetpunten geven goede waarden.
- De afvoeren zijn behoorlijk stabiel, op twee lokaties na (kmr 919 en 947). Slingering maximaal 1 m3/s.

4000 m3/s Lobith
- Waterstanden zijn zeer stabiel.
- De afvoeren zijn behoorlijk stabiel, op een paar lokaties na. Slingering maximaal ca 1 m3/s. Uitzondering is raai 946, slingering 30 m3/s. Dit komt waarschijnlijk door een neer.

6000 m3/s Lobith
- Waterstanden zijn behoorlijk stabiel. Rond kmr 929 (924 – 933) treedt een slingering op, maximum is 4 mm op kmr 929. Ook op kmr 883 treedt een slingering op, van 3 mm.
- De afvoeren zijn behoorlijk stabiel. Rond kmr 929 (924 – 933) treedt een slingering op, maximum is 130 m3/s op kmr 929. Ook op kmr 883 en 947 treden slingeringen op, van resp. 1 m3/s en 1.5 m3/s.
- De slingeringen rond kmr 929 zijn het gevolg van het Amsterdam Rijnkanaal; raai 929 ligt hier precies doorheen. Aan beide zijden van het zomerbed treden neren op, bovendien ligt er een lateraal. Dit is nu niet op te lossen.
- Van de slingeringen rond km 883 en 947 is de oorzaak nog onbekend, nu niets aan te doen.

8000 m3/s Lobith
- Waterstanden zijn zeer stabiel.
- De afvoeren zijn behoorlijk stabiel, op een paar lokaties na (kmr 919 en 947). Slingering maximaal ca 1 m3/s.

10000 m3/s Lobith
- Waterstanden zijn zeer stabiel.
- De afvoeren zijn zeer stabiel.

16000 m3/s Lobith
- Deze berekening hebben we nogmaals bekeken.
- Waterstanden zijn zeer stabiel.
- De afvoeren zijn zeer stabiel, met uitzondering van de bekende instabiliteit op de Boven-Rijn (maximum op kmr 864 en 865, ca 10 m3/s). Hier is nu niets aan te doen.

18000 m3/s Lobith
- Waterstanden zijn behoorlijk stabiel, een aantal lokaties slingert licht (max 1 mm).
- De afvoeren zijn zeer stabiel, met uitzondering van de bekende instabiliteit op de Boven-Rijn (maximum op kmr 864 en 865, ca 40 m3/s). Hier is nu niets aan te doen.

Met vriendelijke groet,

Dénes
Tijmen

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Friday, February 28, 2014 6:30 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL)
Subject: RE: computation of NDR with fixed HPleij

Migena,

We hebben naar de herberekening van NDRLK gekeken. Hierbij onze opmerkingen:
- Algemeen: naam regelwerk Hondsbroeksche Pleij is niet zichtbaar in Waqview => in bestand kunstwerk-p_handm moet een naam komen vergelijkbaar met de naam in kunstwerk-l (...., name='Regelwerk Hpleij 01 ').
- Al eerder opgemerkt (bij splitsingspuntenmodel): definitie puntbarriers Hpleij: zoals het nu is, is het niet fout (WAQPRE accepteert het immers), maar niet duidelijk. De barriers liggen nu namelijk om en om (als gevolg van de verfijning) in plaats van in één serie. Gevraagd wordt om in de siminp de definitie van de barriers aan te passen, zodanig dat ze in een serie liggen. De definities van de punten (die Baseline maakt) hoeft dus niet te worden aangepast.
- Waterstanden en afvoeren zeer stabiel, mooi!
- De afvoerverdeling ziet er goed uit, want is gelijk aan die in het splitsingspuntenmodel. De afvoer op de IJssel is beide modellen 2 m3/s te klein (2.459 m3/s i.p.v. 2.461 m3/s) maar dit accepteren we.
- Q-raaien hoogwatermeting eruit (5x), q-raai waal 877 eruit, q-raaien zombed eruit (4x).

Hiermee kunnen de berekeningen van de overige afvoeren voor NDRLK gemaakt worden.

…

Met vriendelijke groet,

Dénes
Tijmen

C.4 IJssel model

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Monday, August 11, 2014 1:10 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL)
Subject: RE: IJssel other discharge computations

Migena,

We hebben naar de overige afvoeren voor de IJssel gekeken. Onze conclusies staan hieronder, per afvoerniveau. Over het algemeen zien de modellen er zeer goed uit qua stabiliteit, complimenten! We gaan akkoord met de modellen. Ook voor deze deelmodellen (en die van de Waal) geldt dat we de SIMINP's nog willen aanvullen. Wij zullen daarbij ook de definities en namen van de pointbarriers hard in de SIMINP opnemen, zoals eerder besproken.

<u>600 m3/s Lobith</u>
- Redelijk stabiel, wat opvalt is dat het waterniveau in sommige stations nog licht zakt (gaat om tienden van mm, maar toch), kleine slingering in afvoer op een aantal plaatsen, max 2 m3/s.
- Dit heeft waarschijnlijk ook te maken met te hoge initële waterstand in plassen en het flauwe verhang op de beneden-IJssel, hoe is het initiële veld in deze berekening bepaald? Zou de berekening daarvoor langer moeten duren?
- Wat verder opvalt is dat de meetpunten Pannerdensche Kop en Looveer droogvallen. Hier moeten we in j15_5 naar kijken, nu niets aan te doen.
- De initiële waterstanden in aangetakte plassen passen niet bij hele lage afvoeren. Oplossing vergt een aanpassing van Waqini, nu niets aan te doen. We hebben hier wel een idee dat we nog als wens voor KPP2015 zullen opsturen.
- Het leeglopen van aangetakte plassen is nog lang niet voltooid. Dit gaat erg langzaam, maar dit ligt voor een deel ook aan de schematisatie. Nu niets aan te doen.

<u>1020 m3/s Lobith</u>
- Zeer stabiel, op een kleine slingering in een aantal waterlevelstations rond km-raai 950 na (max 0,5 mm) en een kleine slingering in afvoer op een aantal plaatsen (max 0,6 m3/s), geen probleem.
- Wat verder opvalt is dat meetpunt Looveer nog steeds droogvalt. Hier moeten we in j15_5 naar kijken, nu niets aan te doen.

<u>2000 m3/s Lobith</u>
- Zeer stabiel. Kleine slingering in afvoer (max 0,5 m3/s), geen probleem.

<u>4000 m3/s Lobith</u>

- Zeer stabiel. Kleine slingering in een paar waterlevelstations (max 1 mm), geen probleem.

<u>6000 m3/s Lobith</u>
- Zeer stabiel.

<u>8000 m3/s Lobith</u>
- Zeer stabiel. Kleine slingering in afvoer (max 1 m3/s), geen probleem.

<u>10.000 m3/s Lobith</u>
- Zeer stabiel.

<u>18.000 m3/s Lobith</u>
- Redelijk stabiel, in het splitsingspuntengebied en rond Doesburg slingeringen in waterstand en afvoer, tot max 4 mm en 5 m3/s, oorzaak in splitsingspuntengebied waarschijnlijk dicht regelwerk Pannerden dat ook nog overstroomt, oorzaak Doesburg nog niet bekend.
- We twijfelen of de keus voor afregelen afvoerverdeling bij 18.000 m3/s met behulp van het regelwerk Pannerden de juiste is. Moet eigenlijk met rivierverruiming gepaard gaan, anders lukt het niet de gewenste afvoer richting de Waal te krijgen.
- Hier kan nu niets aan gedaan worden, **als we de deelmodellen opnieuw maken willen we hier beter over nadenken en dit bespreken**. Een mogelijkheid is om in de drie takmodellen de gewenste afvoerverdeling op te leggen als onttrekking, in combinatie met een vaste instelling van de regelwerken. Het splistsingspuntenmodel wijkt dan af, maar dan zijn er tenminste modellen van elke tak met de gewenste afvoer.

Met vriendelijke groet,

Dénes
Tijmen

From: Vos, Tijmen (ON) [mailto:tijmen.vos@rws.nl]
Sent: Friday, February 28, 2014 6:30 PM
To: Migena Zagonjolli
Cc: Beyer, Dénes (ON); Scholten, Martin (WVL)
Subject: RE: computation of NDR with fixed HPleij

Migena,
…
We hebben tevens naar de herberekening gekeken van de MHW voor de IJssel (alleen de som met vast regelwerk Hondsbroeksche Pleij). Onze opmerkingen:

- Q-raaien hoogwatermeting eruit (5x), q-raaien zombed eruit (1x).
- Opmerkelijk is dat de afvoer door de IJssel in deze som wel 2.461 m3/s is.
- Ziet er verder goed uit.

Hiermee kunnen de berekeningen van de overige afvoeren voor de IJssel ook gemaakt worden.

Met vriendelijke groet,

Dénes
Tijmen

D Toepasbaarheid van kleine roostercellen in WAQUA voor overlaten

Memo

Deltares

Aan
Martin Scholten; Rijkswaterstaat Water, Verkeer en Leefomgeving

Datum	**Kenmerk**	**Aantal pagina's**
29 november 2013	1207880-006-ZWS-0009	5
Van	**Doorkiesnummer**	**E-mail**
Erik de Goede	+31 (0)88 33 58 475	erik.degoede@deltares.nl

Onderwerp
Toepasbaarheid van kleine roostercellen in WAQUA voor overlaten

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Datum	Auteur	Paraaf	Review	Paraaf	Goedkeuring	Paraaf
nov. 2013	E.D. de Goede	EdG.	A. Spruyt	[signature]	F. van der Knaap	[signature]
	J. van Kester	[signature]	M. Zagonjolli			

1 Doel van memo

In het kader van het KPP project "Gebiedschematisatie zoet" is aan Deltares de volgende vraag voorgelegd (email van Martin Scholten, d.d. 23 september 2013; Deelmodellen Rijn v6.doc):

> *Er moet nog een uitspraak / advies van Deltares komen over de toepasbaarheid i.v.m. de kleine roosterafmetingen (vraagpunt betreft de wijze waarop overlaten in WAQUA worden afgehandeld – subgrid – en de consequenties die dit heeft voor vergunningverlening: worden de juiste effecten uitgerekend als het energieverlies van een overlaat in één heel kleine cel wordt opgelegd).*

In dit memo probeert Deltares deze vraag zo goed mogelijk te beantwoorden. Deze vraag dient beantwoord te worden voor modelschematisaties met een roosterresolutie van zo'n 20 m. Voor bijvoorbeeld de Maas en de Rijn worden momenteel deelmodellen met een dergelijke resolutie opgezet. Globaal gezien is de resolutie van deze detailmodellen zo'n 20 m. Door het gebruik van kromlijnig orthogonale roosters komen lokaal in de binnenbochten van de rivieren kleinere roostercellen voor, van ongeveer 10 m. De vraagstelling is of voor dergelijke kleine roostercellen een subgrid benadering van overlaten, zoal geïmplementeerd in WAQUA nog wel toegepast mag worden. De vraagstelling betreft de voorspelling van het effect van een ingreep in het stromingsgebied van een rivier op waterstanden en afvoeren voor een rivierengebied met overlaten (kribben, zomerdijken).

Als zo'n subgrid aanpak niet meer geschikt is op een rooster met een lokale verfijning, dan dient door Deltares beschreven te worden wat er dan niet goed meer is. Berekent het model een te groot energieverlies, zodat de waterstand eigenlijk te hoog wordt voorspeld? Of is het energieverlies te klein, zodat de waterstand te laag voorspeld wordt? Als het energieverlies moet worden weergegeven over de lengte van één rekencel die bovendien kleiner is, dan is er wellicht een grotere gradiënt dan in werkelijkheid (NB. De lengte van het horizontale beïnvloedingsgebied van een krib is zo'n zeven keer de hoogte van een krib).

2 Achtergrondinformatie

2.1. Toetsing in het Rivierkundig Beoordelingskader

De huidige modellen in het zogeheten 'Rivierkundig Beoordelingskader' zijn momenteel gebaseerd op een roosterresolutie van zo'n 20 bij 10 meter en worden gebruikt in de 'vergunningsverlening'. Het gaat hierbij om relatieve verschillen. Absolute waterstanden doen er minder toe. Het gaat om de beoordeling van effecten van ingrepen, waarbij getoetst wordt op:

- Hoogwaterveiligheid.
- MHW waterstand in de as van de rivier en buiten de as van de rivier.
- Afvoerverdeling bij MHW en normaal hoogwater.
- Hinder of schade.
- Waterstanden in de uiterwaard.
- Stroombeeld in hoofdgeul en uiterwaard, zowel stroomrichting als snelheid.
- Afvoerverdeling bij lage afvoeren.

2.2. Type van modellering in Simona

In Simona zijn er in principe twee concepten voor modellering van een kunstwerk mogelijk, te weten de zogeheten 'overzichtsmodellering' en 'detailmodellering', zie de technische documentatie van Simona (Rijkswaterstaat, 2012) en Zijlema (2000). Een kunstwerk (krib, dijk of barriër) zorgt voor een reductie van het doorstroomoppervlak in het horizontale of verticale vlak. Deze reductie zorgt lokaal voor hogere stroomsnelheden. Overzichtsmodellering kan beschouwd worden als 'globale modellering'. Het rooster is dan te grof om de reductie van het doorstroomoppervlak te kunnen beschrijven. Dit houdt in dat waterstanden en debieten wel nauwkeurig berekend kunnen worden, maar de lokale snelheden in de buurt van deze kunstwerken niet. Omdat de snelheden lokaal onjuist zijn, kunnen ook de energieverliezen t.g.v. de contractie en daarop volgende expansie niet nauwkeurig berekend worden met een geschikt advectieschema, zie Stelling en Duinmeijer (2003).

Door de grofheid van de toegepaste rekenroosters rond kunstwerken wordt voor de modellering van rivieren met WAQUA al jaren de *overzichtsmodellering* toegepast. De energieverliezen t.g.v. overlaten worden geparameteriseerd op basis van het zogenaamde Rijkswaterstaat' Tabellenboek in rekening gebracht. Dit Tabellenboek is de vertaling van de empirische kennis uit modelproeven. Enige jaren geleden is overigens aan WAQUA een energieverliesformulering op basis van de Villemonte-relatie toegevoegd, die het mogelijk maakt ook rekening te houden met de geometrie van een krib. Dit is overigens nog steeds een toepassing van overzichtsmodellering.

Bij '*detailmodellering*' wordt een zeer fijnmazig rooster toegepast en kan de reductie van het doorstroomoppervlak bij een kunstwerk wel op het rekenrooster beschreven worden. Dit houdt in dat een krib, dijk of barriër in de bodemschematisatie is opgenomen. De twee concepten van '*overzichtsmodellering*' en '*detailmodellering*' in relatie met riviermodellering worden ook beschreven in het BSc-werk van Maljaars (2013).

Een aantal jaar geleden is er door Yossef en Zagonjolli (2010) met WAQUA een principetest met *detailmodellering* uitgevoerd voor een riviermodel met kribben. Hierbij is een rekenrooster met een resolutie van twee meter toegepast voor een geschematiseerd deel van een rivier (met een aantal kribben). Dit leverde bijzonder lange rekentijden op, maar is tot op heden de eerste en enige test met detailmodellering voor een WAQUA riviermodel. Voor deze situatie bleken door WAQUA met '*detailmodellering*' kleinere verliezen berekend te worden voor de kribben dan met '*overzichtsmodellering*' in combinatie met een subgrid overlaatformulering. Dit is terug te voeren op de eigenschappen van het numerieke advectieschema, dat toegelicht zal worden in de volgende paragraaf.

2.3. Eisen aan een numeriek schema m.b.t. modellering van een krib/overlaat

In de expansiezone na een krib/overlaat treedt energieverlies op. Het numerieke advectieschema in WAQUA is energiebehoudend, zowel voor convergerende als voor divergerende stroming. Daarom zal dit numerieke schema geen energieverliezen berekenen voor een expanderende stroming ook niet op een fijnmazig rooster. Voor de expansiezone is een impulsbehoudend advectieschema vereist, zoals beschreven in Stelling & Duinmeijer (2003). Het is overigens een grote aanpassing van het rekenschema van WAQUA om de huidige tweestaps impliciete tijdsintegratiemethode voor advectie, om te zetten naar een expliciete impulsbehoudende advectiemethode.

Als de roosterresolutie verder verkleind wordt, dan is de subgrid aanpak voor overlaten/kribben niet meer van toepassing. De roosterafstanden moeten dan nog wel een orde fijner worden dan de nu toegepaste rekenroosters voor de detailmodellen. Een krib of dijk moet dan zo'n vijf tot tien roostercellen breed zijn. Dit resulteert in rekenroosters in de orde van enkele meters.

3 Beantwoording van de vraagstelling

3.1. Conclusies

In de huidige Rijkswaterstaat praktijk wordt bij de modellering met WAQUA voor rivieren altijd *overzichtsmodellering* toegepast. Bij de huidige modelschematisatie van de deelmodellen met minimale roosterafstanden van zo'n 10 tot 20 m, kan nog niet van *detailmodellering* gesproken worden. ***Daarom is Deltares van mening dat de huidige subgrid-aanpak voor een krib/overlaat hiervoor geschikt is en dat deze formuleringen dus toegepast mogen worden.*** We adviseren wel om deze uitspraak verder te toetsen met een zogenaamde roosterconvergentiestudie, zie Paragraaf 3.2.

Tevens dient de vraag beantwoord te worden wat er niet goed is als de subgrid-aanpak niet meer geschikt is. Deze vraag is niet van toepassing, omdat de subgrid-aanpak wel geschikt en dus toegepast kan worden voor modellen met roosterafstanden van zo'n 10 tot 20 m.

Als de subgrid-aanpak beoordeeld zou moeten worden voor situaties die zich lenen voor detailmodellering (d.w.z. roosterafstanden van een paar meter), dan is het lastig hierover op voorhand een uitspraak te doen. Van het huidige advectieschema in WAQUA is bekend dat er geen energieverlies berekend wordt voor een expanderende stroming. Hierdoor ligt het voor de hand dat WAQUA een te lage waterstand zal berekenen. Bij het hierboven voorgestelde roosterconvergentiestudie kan dit onderzocht worden.

Voor de volledigheid en wellicht ten overvloede, met deze *overzichtsmodellering* op een dergelijk rooster kunnen alleen waterstanden en debieten in de nabijheid van een krib of overlaat nauwkeurig berekend worden. Dit geldt dus niet voor de snelheden/stroombeelden op of zeer nabij een krib/overlaat, zie Maljaars (2013), hiervoor is *detailmodellering* nodig. Dit laatste betekent een rekenrooster in de orde van enkele meters. Hiervoor is momenteel geen geschikt advectieschema beschikbaar in Simona.

3.2. Aanbevelingen

Deltares beveelt aan om dit aspect van roosterconvergentie verder te onderzoeken door de simulatie van de stroming over een overlaat met WAQUA voor een geschematiseerde 1D-kanaalstroming in combinatie met verschillende rekenroosters rondom een overlaat. Deze rekenroosters kunnen ook 2D zijn.

Verder willen wij opmerken dat bij Deltares gewerkt wordt aan de ontwikkeling van de zogenaamde Next Generation Hydro Software (NGHS, 2013), wat in samenwerking met Rijkswaterstaat wordt uitgevoerd. Een belangrijk onderdeel van de NGHS is het stromingsmodel D-Flow Flexible Mesh. In D-Flow Flexible Mesh worden de ondiepwatervergelijkingen gediscretiseerd op een ongestructureerd rekenrooster. Hierbij is er een numeriek schema voor advectie ingebouwd dat rekening houdt met de lokale eigenschappen van de stroming, zoals beschreven door Stelling en Duinmeijer (2003). Door Kramer en Stelling (2008) is deze methode gegeneraliseerd naar een ongestructureerd rekenrooster. Met D-Flow Flexible Mesh is er al onderzoek uitgevoerd naar de roosterconvergentie voor de simulatie van de stroming over een overlaat bij een dieptegemiddelde (2D) toepassing. Daarom zou D-Flow Flexible Mesh een rol kunnen spelen bij het hierboven voorgestelde onderzoek naar roosterconvergentie.

4 Referenties

Kramer, S.C., Stelling, G.S., 2008. A conservative unstructured scheme for rapidly varied flows. International Journal for Numerical Methods in Fluids 58 (2), 183– 212

Maljaars, J.M., 2013. Stroomsnelheden rond kribben. Vergelijking van WAQUA-modelresultaten met metingen. BSc thesis. Technische Universiteit Delft.

NGHS, 2013. http://publicwiki.deltares.nl/display/nghs/Next+Generation+Hydro+Software.

Rijkswaterstaat, 2012: Technical documentation WAQUA/TRIWAQ. two- and three-dimensional shallow water flow model Simona report nr. 99-01. Version 3.16. March 2012.

Stelling, G., Duinmeijer, S., 2003. A staggered conservative scheme for every Froude number in rapidly varied shallow water flows. International Journal for Numerical Methods in Fluid 43 (12), 1329–1354.

Yossef, M., Zagonjolli, M., 2010. Modelling the hydraulic effect of lowering the groynes on design flood level. Deltares 1002524-000-ZWS-0009.

Zijlema, 2000. Modellering van de sluis, Implementatie van een vernieuwde 3D sluisformuleringen TRIWAQ voor gedeeltelijk geopende sluizen. Project Nautilus, RIKZ/OS/2000.106X.

5 Bijlage 1: Detail- en overzichtsmodellering voor sluizen

In (Zijlema, 2000) wordt ingegaan op detail- en overzichtsmodellering voor sluizen. Deze studie had toentertijd vooral betrekking op het modelleren van de Haringvlietsluizen met driedimensionale modellen. In dit rapport wordt geconcludeerd (zie pagina 6) dat met betrekking tot sluizen:

- WAQUA alleen een overzichtsmodellering kan toepassen; en dat
- met TRIWAQ wel zowel detail- en overzichtsmodellering mogelijk is. Bij TRIWAQ is detailmodellering mogelijk, omdat een zogeheten '3D barrierformulering' is ingebouwd en lokaal rond de sluis de discretisatie van de advectietermen is aangepast.

Dit houdt ook in dat met WAQUA geen detailmodellering mogelijk is. De reden is dat er hiervoor geen aangepast numeriek advectieschema is ingebouwd. Hierbij willen wij toevoegen dat met TRIWAQ weliswaar detailmodellering mogelijk is rondom sluizen, maar dat dit nog niet het geval is voor kribben en overlaten. Samengevat, zowel met WAQUA als met TRIWAQ is op dit moment geen detailmodellering mogelijk voor kunstwerken.