Resources of groundwater, harmonized at Cross-Border and Pan-European Scale

Deliverable 3.4

Harmonisation of volumes, water balances and recharge and discharge fluxes

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1 INTRODUCTION

The cross-border demonstration project H3O-PLUS intends to set a new standard for harmonization across borders, not only for hydrostratigraphy, but also for hydrological data such as groundwater heads and groundwater quality. H3O-PLUS, WP3 of GeoERA RESOURCE, aims to be an advanced demonstration of a transboundary assessment of groundwater resources. It is 'advanced' in the sense that it builds on and extends previous work, trying to make it more useful for groundwater policy and management and for subsurface spatial planning. A 3D hydrogeological model was developed in a series of so called H3O-projects[1] in the transboundary region around the Roer Valley Graben, comprising parts of Germany, the Netherlands and Belgium. The model contains 3D maps of the top, base and thickness of aquifers and aquitards. H3O-PLUS aims to add attribute data to these maps to facilitate the use of the maps in decision making processes. Note that the project does not aim to produce new maps or spatial delineations. The objective is to characterize units on existing maps and hence support the interpretation and use of those existing maps.

The overall study area coincides with the study areas of previous H3O projects (Figure 1.1). Vertically, the study is limited to the clastic (hydro)geological layers of Cenozoic age or younger. This coincides with the vertical scope of the recently developed transboundary 3D (hydro)geological models of the H3O projects. The base of the models is thus located at the top of the Chalk aquifer (Houthem or Maastricht / Kunrade Formations) or the top of the Carboniferous deposits.

[1] For more information and data downloads of the H3O-projects, the reader may refer to H3O-Roerdalslenk (TNO website), H3O-Roerdalslenk (website of the Flemish administration), H3O – De Kempen (TNO website), or H3O-De Kempen (website of the Flemish administration).

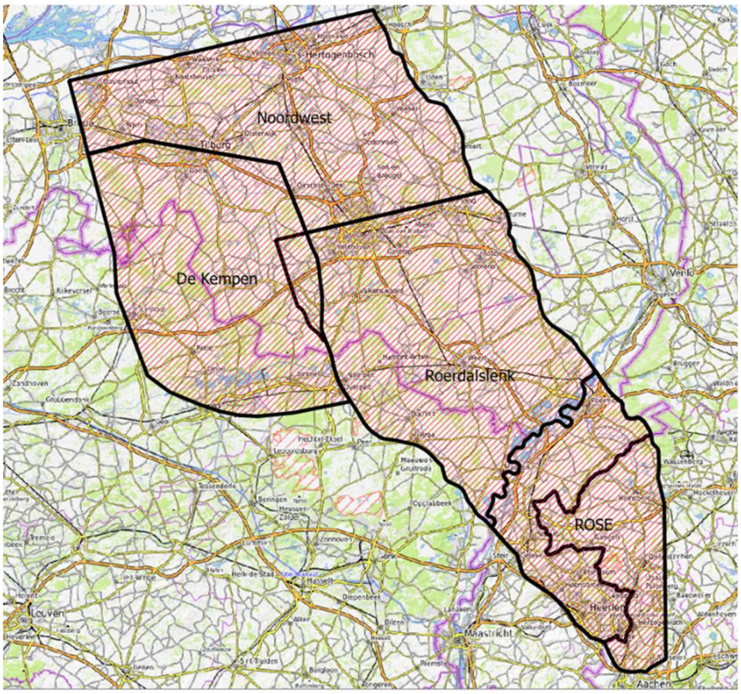


Figure 1.1. Study areas of previous H3O projects (note the label "Roerdalslenk" can be translated to "Roer Valley Graben").

This report describes a cross-border analysis of the water balance of the groundwater system in the Roer Valley Graben. The total volumes of water, recharge fluxes and recharge and discharge routes (abstractions, seepage) were assessed for the most important aquifers in the cross-border region. The underlying objective of the reported analysis is to contribute to the development of integrated groundwater management strategies on different sides of common borders.

Hereafter, the Roer Valley Graben will be referred to as "RVG". All references made to geological units according to the H3O-nomenclature, are based on Table 2 of the end report of the H3O-Roerdalslenk project (Deckers et al., 2014).

2 METHODOLOGY

2.1 Principal tool: groundwater model

2.1.1 Overview of groundwater models in the Roer Valley Graben

Numerical groundwater models are the most suitable tools for quantifying water balances and fluxes in complex geohydrological systems like the Roer Valley Graben. Over the past decades, several regional groundwater models have been developed for different parts of the RVG and adjacent regions:

- the Brabant model for the Dutch province of Noord-Brabant (Verhagen et al., 2017; Verhagen et al., 2019);
- the IBRAHYM model for the Dutch province of Limburg (Vermeulen et al., 2015);
- the CKS model for the Central Campian System in Belgium, west of the RVG (De Smedt et al., 2007-1);
- the MS model for the Meuse Valley in Northeast Belgium (Severyns & De Smedt, 2006; De Smedt et al., 2007-2);
- the groundwater model for the lignite mining area in North Rhine Westphalia (RWE AG, 2013).

While the aforementioned models cover specific parts of the RVG and adjacent areas, a groundwater model covering the entire RVG has been developed in recent years (Vermeulen & Op den Kelder, 2020). This model, built by research institute Deltares and commissioned by a cross-border consortium of water authorities in the RVG, will be referred to hereafter as IBRAHYM-ROERDAL. Given its large model extent and recent development, with involvement of water authorities from Belgium, Germany and The Netherlands, IBRAHYM-ROERDAL was chosen as the main tool for the quantification of water balances and fluxes in the RVG.

Being a relatively new model, IBRAHYM-ROERDAL may be considered to be in a less mature state than some of the aforementioned regional groundwater models. An update of the model will be carried out in 2021, relating to different aspects of the groundwater system. Among these is the desire for a more uniform hydrogeological model, which in the current version is the result of a compilation of different hydrogeological models showing discontinuities at their interfaces. This should be taken into account when reading and interpreting the findings in this report.

2.1.2 The IBRAHYM-RVG model

IBRAHYM-ROERDAL is based on the Dutch version of the IBRAHYM model (version 2, Vermeulen et al., 2015). Its hydrogeological model is based on results from the H3O-projects that were available at the time of development. *Figure 2.1* shows the spatial extent of the applied version of IBRAHYM-ROERDAL. The model has a spatial resolution (cellsize) of 250 x 250 m^2, and 20 model layers extending from the land surface down through H3O-units 0252 and 0253, also known as Breda or Diest/Bolderberg/Ville

Formation. As shown in *Figure 2.1*, fixed hydraulic heads (Dirichlet open boundary conditions) are imposed on parts of the south eastern boundary of the model. Closed boundaries are imposed on the remainder of the model boundaries except for a small stretch to the east of Heerlen, which is modelled as a constant flux (Neumann) boundary (not shown in *Figure 2.1*).

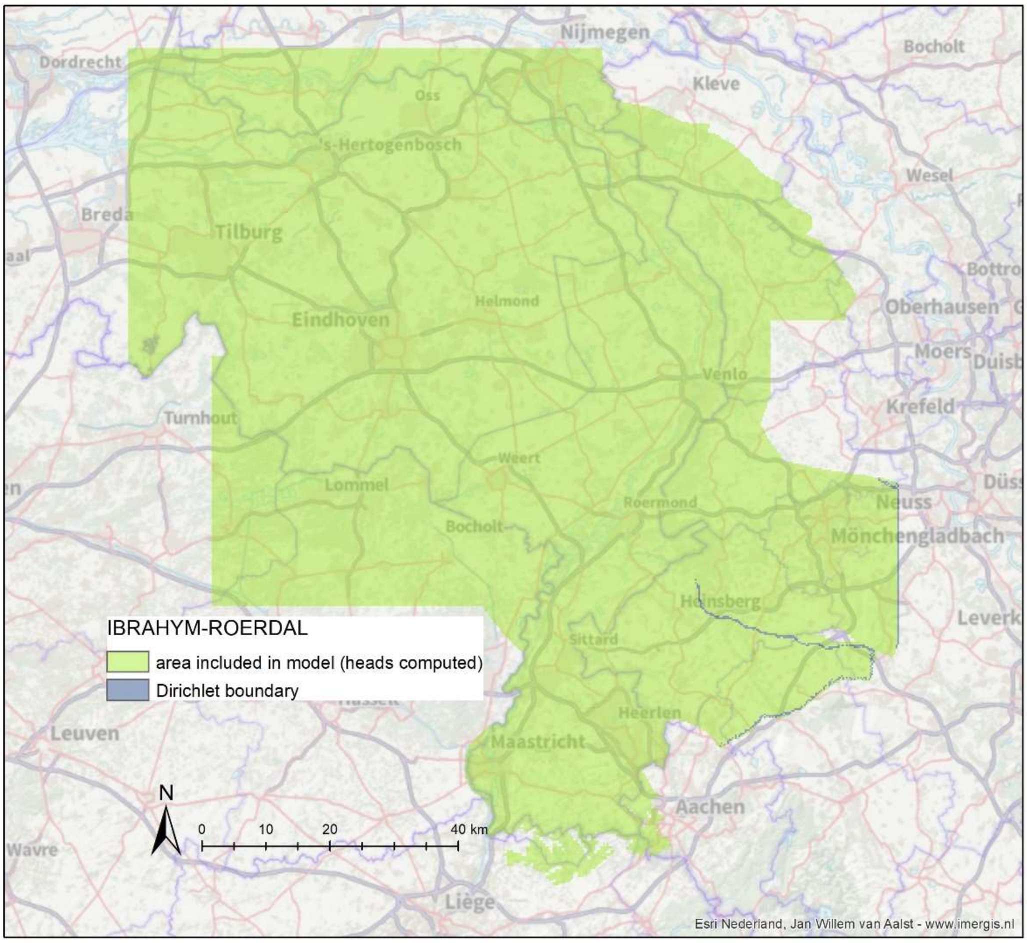


Figure 2.1. Spatial extent of the IBRAHYM-ROERDAL groundwater model.

Figure 2.2 shows a cross-section of the hydrogeological model of IBRAHYM-ROERDAL, extracted from the DIS-package provided with the model input. The cross-section shows the relations between model layers and hydrogeological units. The cross-sections shows how the 20 model layers concur with known REGIS v2.2 and/or H3O hydrogeological units.

Figure 2.2 highlights the fact that the top of H3O-units 0252 and 0253 - the Breda or Diest/Bolderberg/Ville Formation as compiled from existing H3O-project models - cuts across different model layers. These units have a marine origin and are partly brackish, notably in Noord-Brabant. For some groundwater management purposes, e.g. aimed at compliance to the European Water Framework Directive (WFD), it may therefore be more convenient to consider these units as geohydrological basis, rather than the

IBRAHYM-ROERDAL model basis. The different implementations of the concept of geohydrological basis - as applied in IBRAHYM-ROERDAL on one hand, and as considered for e.g. WFD compliance on the other hand - somewhat complicates the assessments presented in this report, notably of groundwater volumes. In section 3.2 this issue will be illustrated, as an example, for the WFD groundwater body 'Maas Slenk Diep' in the Dutch part of the RVG (Provincie Noord-Brabant, 2015).

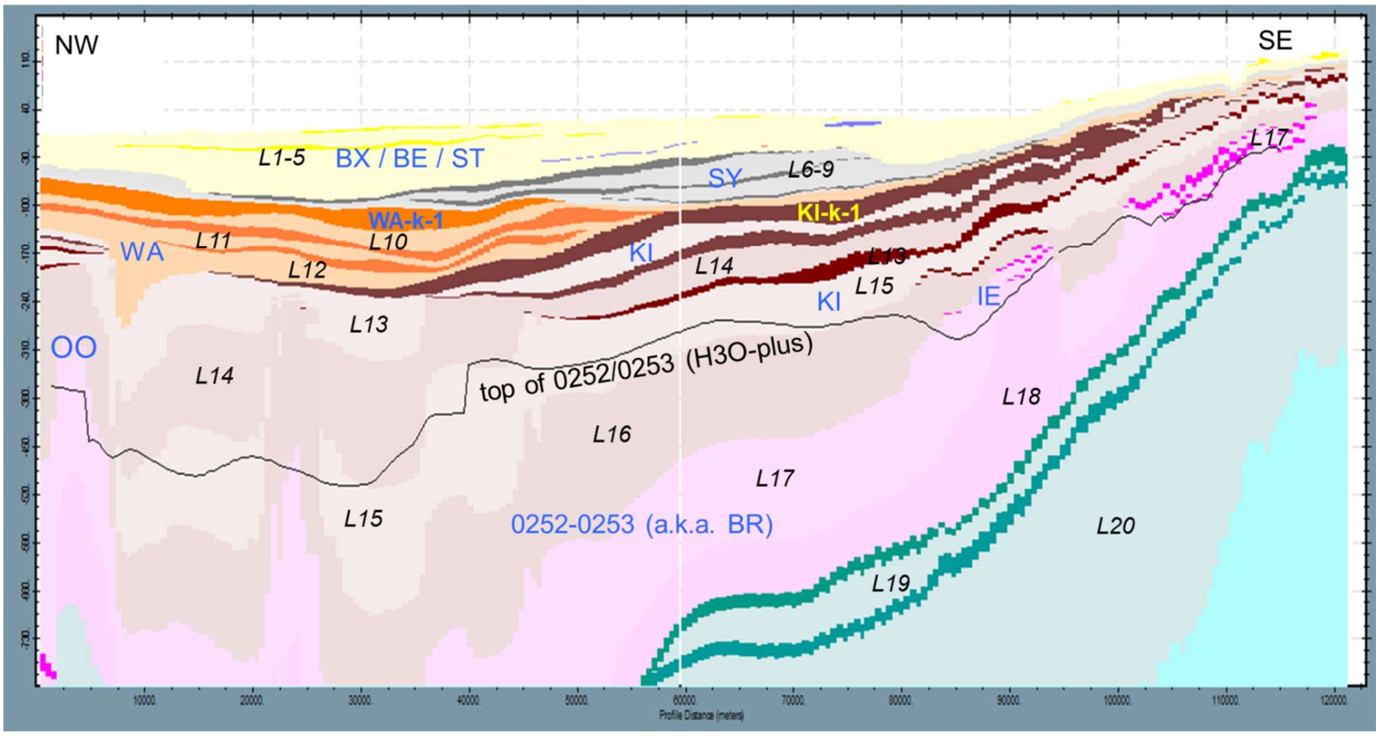


Figure 2.2. Cross-section of the hydrogeological model of IBRAHYM-ROERDAL, along the full length of the RVG (northwest to southeast). In blue text: geological units in H3O-nomenclature. In italic text: model layer numbers. Black line: top of H3O-unit 0252/0253 (Breda or Diest/Bolderberg/Ville Formation), compiled from existing H3O-models and inferred geohydrological basis for some groundwater management purposes. Also shown are the main aquitards covering the deep RVG: WA-k-1 and KI-k-1.

IBRAHYM-ROERDAL was built and is operated with the software package iMOD (Interactive MODeling, Vermeulen, *et al.*, 2019). iMOD is an interactive modelling tool to be used with the groundwater modelling code MODFLOW (McDonald & Harbaugh, 1988). It provides the necessary functionalities to manage groundwater flow models efficiently, including the generation of water balances and fluxes. These features are essential in the current analysis. For details about the construction of IBRAHYM-ROERDAL, see Vermeulen & Op den Kelder (2020).

For the purpose of this study, the model version delivered by Deltares in January 2020, and reported in Vermeulen & Op den Kelder (2020) was used. Simulation output data based on this model version was analysed. The simulation output packages (dated 07-

05-2020) that were eventually used for the analysis, as well as the corresponding input packages (dated 26-05-2020), were provided by RoyalHaskoningDHV, with permission granted by the IBRAHYM-consortium.

2.1.3 Regional groundwater models in the RVG

To gain insight in uncertainties around simulated water balances and fluxes in the RVG, comparisons of the water balance results based on IBRAHYM-ROERDAL were made with results reported for two of the aforementioned regional groundwater models: the Brabant model and the MS model. These comparisons, preceded by brief descriptions of these regional models, are reported in sections 3.3.2 and 3.3.3. respectively.

2.2 Quantification of water balances and fluxes

2.2.1 Aquifer zonation

For the quantification of water balances and fluxes, the RVG was vertically divided into a shallow aquifer and a deep aquifer.

In the northwestern part of the province of Noord-Brabant, the clay layer identified as H3O-unit WA-k-1 represents the main aquitard between the shallow and deep aquifer. In Central Limburg (NL), the southeastern part of Noord-Brabant, and the Belgian and German parts of the RVG, the main aquitard between the shallow and deep aquifer is represented by H3O-unit KI-k-1. Both aquitards are represented by different model layers in IBRAHYM-ROERDAL. WA-k-1 is positioned below model layer 9 and above model layer 10, while KI-k-1 is positioned below model layer 12 and above model layer 13 (see *Figure 2.2*). Therefore, different sets of water balances and fluxes were quantified, one set considering WA-k-1 as main aquitard in the entire RVG, and the other set considering KI-k-1 as main aquitard in the entire RVG. These two sets of water balances and fluxes were used for the general analysis reported in sections 3.1 and 3.2. The areal extents of both aquitards in IBRAHYM-ROERDAL are displayed in Figure 2.3.

In addition to the two aforementioned sets, water balances and fluxes were also quantified considering:

- SY-k-1 as main aquitard in the entire RVG, in order to make a proper comparison with water balances and fluxes reported for the Brabant model (see section 3.3.2). SY-k-1 is positioned below IBRAHYM-ROERDAL model layer 6 and above model layer 7;
- KI-k-2 as main aquitard in the entire RVG, in order to make a proper comparison with water balances and fluxes reported for the MS model (see section 3.3.3). KI-k-2 is positioned below IBRAHYM-ROERDAL model layer 13 and above model layer 14;

The definition of shallow and deep aquifer and main aquitard is visualised in *Figure 2.4*.

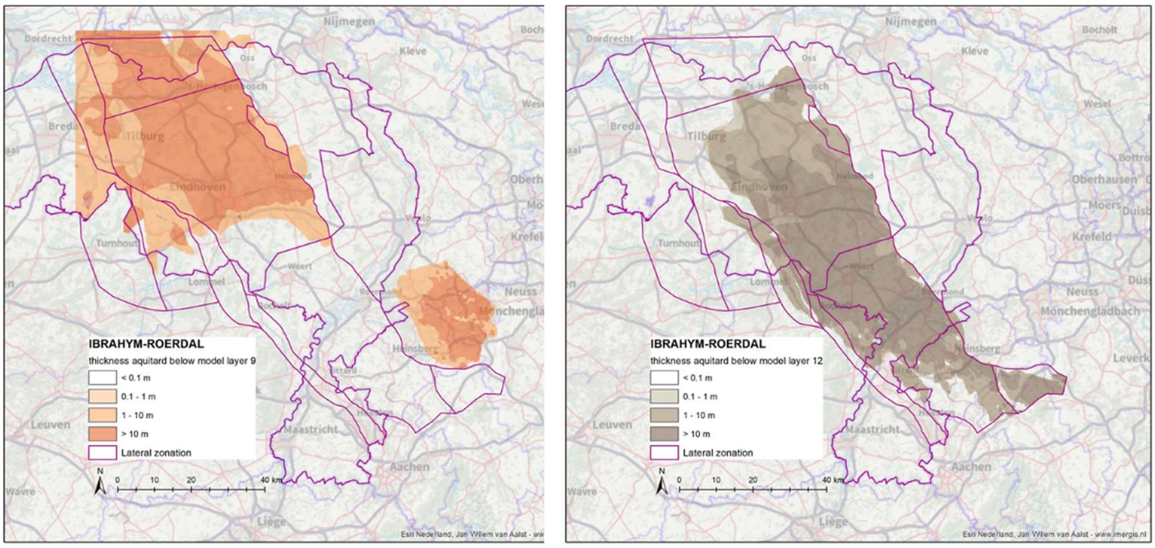


Figure 2.3. Areal extents of IBRAHYM-ROERDAL model layers representing the aquitards WA-k-1 and KI-k-1.

In the analysis to follow in Chapter 3, it is stated that the set with WA-k-1 as main aquitard is relevant for Noord-Brabant and the set with KI-k-1 as main aquitard is relevant for the other RVG zones. It is recognised that this approximation is simplified, because also in the southeastern part of Noord-Brabant KI-k-1 is the main aquitard. With the current geological model, it is however not possible to perform an analysis which is also based on a zonation in administrative boundaries in a straightforward manner.

2.2.2 Water balance terms

The water balances of the aquifers in the RVG can be decomposed into different fluxes (terms) and a storage term. These will be referred to hereafter as water balance terms.

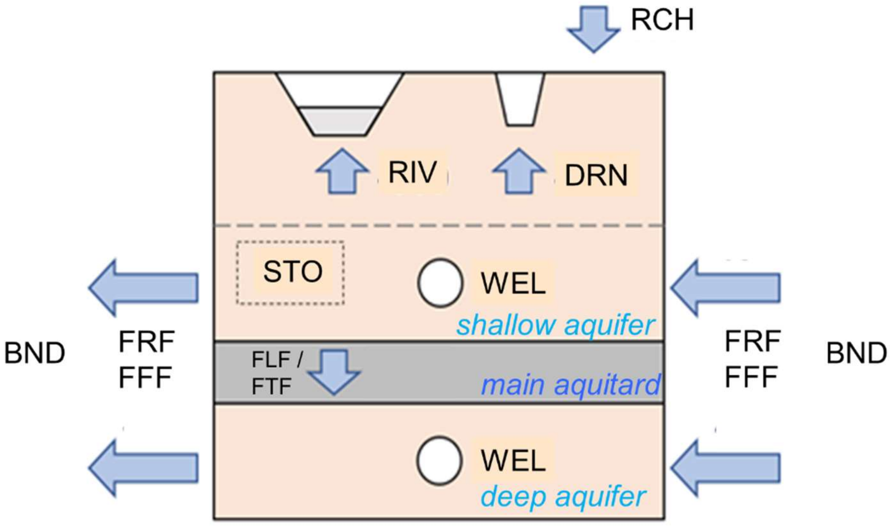


Figure 2.4. Definition of water balance terms, in line with abbreviations of MODFLOW output packages. The format of visualisation was borrowed from Verhagen et al. (2017).

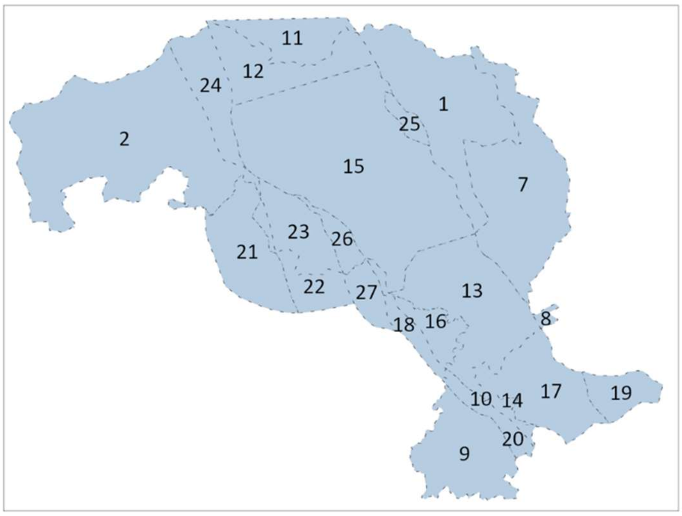
In line with the structure of the output of MODFLOW (the modelling code forming the basis of IBRAHYM-ROERDAL), the following water balance terms can be defined. In brackets are shown the abbreviations of the corresponding MODFLOW output packages, see *Figure 2.4*:

- Flux to/from external model boundaries (BND);
- Fluxes across lateral boundaries defined within the model extent (FFF, FRF);
- Flux across lower boundary (FLF, shallow aquifer only), also referred to as upward or downward seepage, or recharge;
- Flux across upper boundary (FTF, deep aquifer only), also referred to as upward or downward seepage, or recharge;
- Precipitation surplus (RCH, shallow aquifer only);
- Flux to/from large surface waters (RIV, shallow aquifer only);
- Flux to/from small surface waters and tile drains (DRN, shallow aquifer only);
- Flux to/from groundwater abstraction/injection wells (WEL);
- Volume change in phreatic storage (STO, shallow aquifer only).

With respect to fluxes to/from wells, it is noted that in the Dutch part of the RVG, groundwater abstraction for agricultural irrigation is not included in IBRAHYM-ROERDAL.

2.2.3 Lateral zonation

Water balance terms were quantified for specific areas within the RVG and in adjacent areas. These areas will be referred to hereafter as zones. The boundaries between the zones were chosen to coincide with geological faults, and national and provincial borders. The zonation is shown in *Figure 2.5*. On the south western boundary of the RVG, the complex Feldbiss fault system leads to a rather detailed zonation. The analysis of the water balance terms in this report is largely confined to the four zones that comprise the major part of the RVG: the RVG in Noord-Brabant excluding the polder area (zone 15), the RVG in Central Limburg NL (zone 13), RVG Northeast Belgium (zone 16) and RVG Rurscholle (zone 17).



ZONE_ID	Zone name
0	Other areas
1	Peel Block, Noord-Brabant
2	Kempen, Noord-Brabant, West
7	Peel Block and Venlo Block, Limburg
8	Peel Block Meinweg
9	South Limburg
10	Rurscholle (area between faults)
11	RVG, polders Gelderland
12	RVG, polders Noord-Brabant
13	RVG, central Limburg
14	RVG, southeast Limburg
15	RVG, Noord-Brabant
16	RVG, Northeast Belgium
17	RVG, Rurscholle
18	RVG, Northeast Belgium (area between faults)
19	Erftscholle
20	RVG Southeast Limburg (area between faults)
21	Kempen, Northeast Belgium, west of Rauw Fault
22	Kempen, Northeast Belgium, east of Rauw Fault
23	Kempen, Noord-Brabant, Central
24	Kempen, Noord-Brabant, North
25	RVG, Boekel Block
26	Kempen, Noord-Brabant, Westerhoven Block
27	RVG, Northeast Belgium, west of Bocholt Fault

Figure 2.5. Lateral zonation for water balance terms.

2.2.4 Water balance period

Water balance terms were quantified and analysed for the period 2009-2016.

2.2.5 Generation of water balance terms

Water balances were generated with the water balance tool of iMOD version 5.0. This tool calculates the water balance terms described in section 2.2.2 for the zones described in section 2.2.3. These results were generated for each model layer separately, 20 in total, and subsequently aggregated to water balance terms for the shallow and deep aquifer, as defined in section 2.2.1 and shown in *Figure 2.4*. In the geohydrological model input provided with the applied version of IBRAHYM-ROERDAL, H3O-unit WA-k-1 is located below model layer 9 and above model layer 10, and H3O-unit KI-k-1 is located below model layer 12 and above model layer 13. Hence, the aggregation of water balance terms proceeded as follows (see

Table 2.1) :

Table 2.1. Aggregation of water balance terms according to different aquifer definitions.

Main aquitard	Water balance terms aggregated from model layers:	Application / Relevant for area:
WA-k-1	1 - 9 (shallow), 10 - 20 (deep)	NW Noord-Brabant
KI-k-1	1 - 12 (shallow), 13 - 20 (deep)	RVG excl. NW Noord-Brabant
SY-k-1	1 - 6 (shallow), 7 - 20 (deep)	comparison IBRAHYM-ROERDAL with Brabant model
KI-k-2	1 - 13 (shallow), 14 - 20 (deep)	comparison IBRAHYM-ROERDAL with MS model

- In the aquifer definition with WA-k-1 as main aquitard, water balance terms were aggregated from model layers 1 through 9 for the shallow aquifer, and from model layers 10 through 20 for the deep aquifer. These results mainly apply to the northwestern part of Noord-Brabant;
- In the aquifer definition with KI-k-1 as main aquitard, water balance terms were aggregated from model layers 1 through 12 for the shallow aquifer, and from model layers 13 through 20 for the deep aquifer. These results mainly apply to the southeastern part of Noord-Brabant, Central Limburg NL, and the Belgian and German parts of the RVG;
- In the aquifer definition with SY-k-1 as main aquitard, water balance terms were aggregated from model layers 1 through 6 for the shallow aquifer, and from model layers 7 through 20 for the deep aquifer. These results apply to the comparison of IBRAHYM-ROERDAL with results of the Brabant model;
- In the aquifer definition with KI-k-2 as main aquitard, water balance terms were aggregated from model layers 1 through 13 for the shallow aquifer, and from model layers 14 through 20 for the deep aquifer. These results apply to the comparison of IBRAHYM-ROERDAL with results of the MS model.

The aggregation to water balance terms for the shallow and deep aquifer was performed by means of Python 3.7 scripting.

It is noted that rounding issues may cause small deviations between the sums of in- and outgoing fluxes in the presented water balances. It is also worth noting that the unit 'millions of m^3' is often abbreviated as Mm^3.

2.2.6 Calculation of groundwater volumes

Groundwater volumes were calculated for the deep aquifer in each zone by listing model layer thicknesses for all grid cells within the zone, then aggregating them to sums for the shallow and deep aquifers, and finally multiplying the result by the grid cell area (250 x 250 m^2). Again, this was done for different shallow and deep aquifer definitions as described in section 2.2.5. This calculation includes only aquifer volumes; volumes of the aquitards in between are not counted.

Groundwater volumes are presented in this report for the deep aquifers in the four zones that comprise the major part of the RVG (see section 2.2.3). To illustrate the complications provoked by different implementations of the concept of geohydrological basis, as described earlier in section 2.1.2, estimated groundwater volumes are also presented for the WFD-body 'Maas Slenk Diep' in the Dutch part of the RVG.

3 RESULTS

3.1 Water balances and fluxes

3.1.1 Flow directions and reversals

The groundwater flow in the RVG is directed to the northwest, and determined by groundwater recharge in the southeast, and additional inflow from SW and NW directions. As such, the recharge in the most upstream zone, the Rurscholle, is important together with the lateral groundwater fluxes across the Feldbiss and Peelrand fault zones further downstream. These water balance terms are shown in *Figure 3.1* for the set based on the Waalre clay aquitard (Wa-k-1, left figure) and the set with the Kieseloolite aquitard (Kl-k-1, right figure). The Rurscholle may be regarded as the source area of the RVG deep aquifer, recharged by the overlying shallow aquifer, and provides 28 or 26 $Mm^3\ yr^{-1}$ for north-westerly directed flow in the RVG, respectively. The difference between recharge (88 $Mm^3\ yr^{-1}$ / 71 $Mm^3\ yr^{-1}$ respectively) and downstream outflow in this zone (28 $Mm^3\ yr^{-1}$ /26 $Mm^3\ yr^{-1}$ respectively) is mainly caused by groundwater flow out of the model across its southern boundary towards the lignite mining area, which is not relevant for the presented analysis.

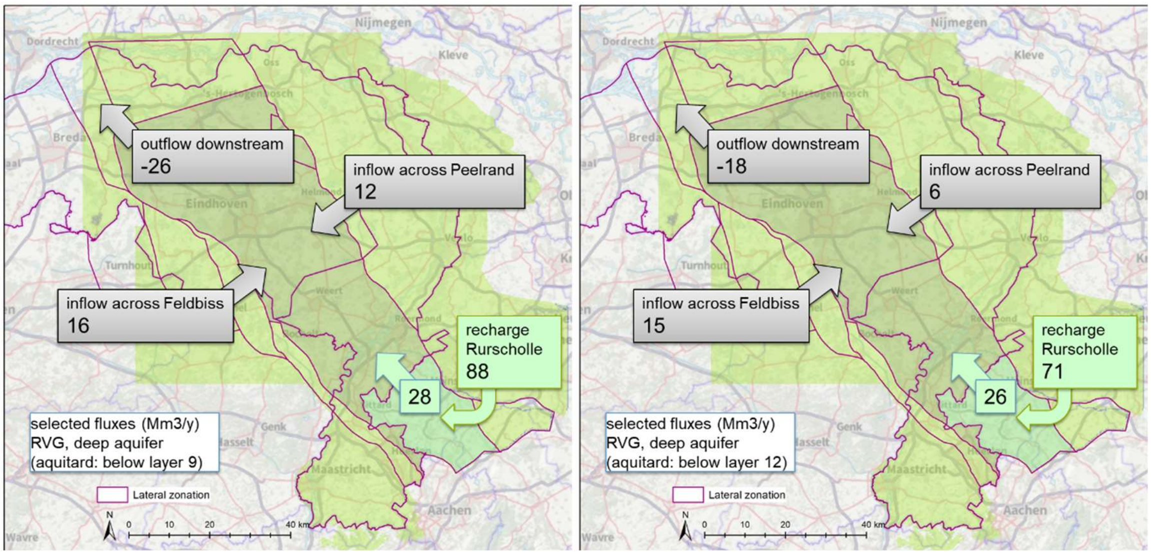


Figure 3.1. Main course of groundwater flow in the deep RVG, in millions of m3 per year. Left: main aquitard positioned below model layer 9, relevant for Noord-Brabant. Right: main aquitard positioned below model layer 12, relevant for other zones. Note: the values do not add up to zero because not all water balance terms are shown.

Further downstream, the NW-directed groundwater flux decreases, despite lateral inflow from the sides across the fault zones. Under natural conditions, the downstream reaches of the deep RVG aquifer may be expected to lose water mainly by upward seepage through the main aquitard, while the upstream part receives water by downward seepage (recharge) (Stuurman et al. 2004, Zuurdeeg et al. 1989, see *Figure 3.2*). The downstream parts of the deep RVG aquifer, however, currently lose groundwater mainly by abstractions. The flow directions between the subsequent aquifers is typically downward, instead of upward which might have been the natural, unaltered situation. In other words, recharge of the deep aquifer from the shallow aquifer occurs.

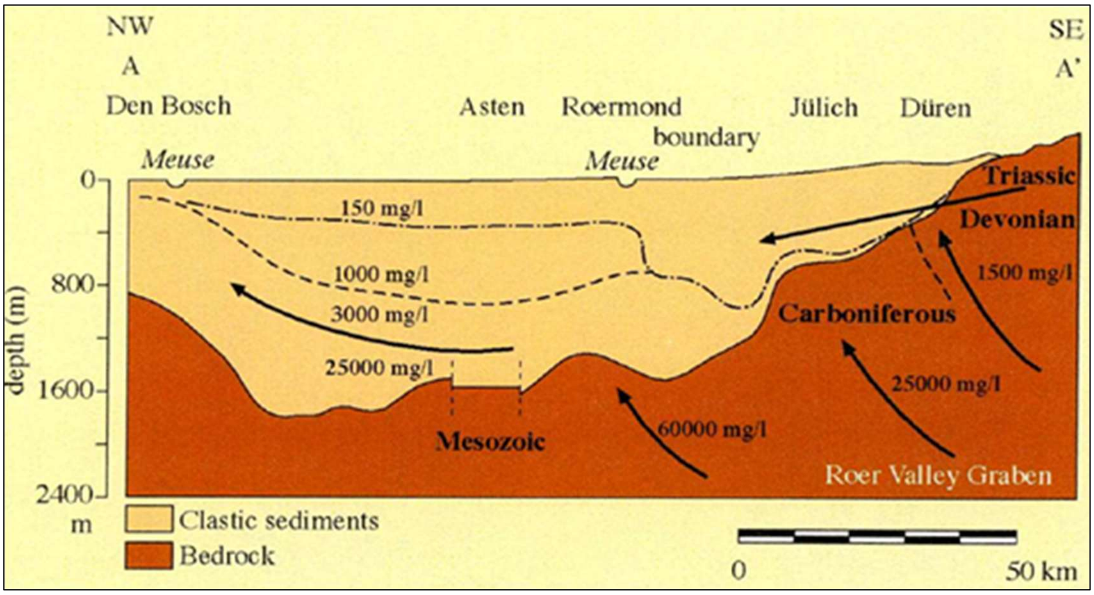


Figure 3.2. Conceptual profile of groundwater flow in the Roer Valley Graben. Taken from Stuurman et al. (2004), original from Zuurdeeg et al. (1989). The ''mg/l'' values represent chloride concentrations.

This flow reversal is also evident from

The same phenomenon of recharge of the deep aquifer from the shallow aquifer is visualised in a different way in *Figure 3.4*. The figure shows the vertical fluxes across the main aquitards in mm/day. Recharge from the shallow aquifer (dominated by Sterksel Formation sands) to the deep aquifer is apparent for the largest part of the RVG in Noord-Brabant, and also apparent for large parts of the RVG in Limburg where recharge is indicated over the Kieseloolite aquitard. The figure shows upward seepage only in the Meuse valley in Limburg and at the downstream end of the RVG, in north-western Noord-Brabant. For the Noord-Brabant part of the RVG, the left figure is most relevant. It shows that the area of upward seepage is limited to 's-Hertogenbosch and the area west of it (Langstraat).

, which shows total water balances for the main zones in the RVG, in millions of m^3 per year. Figure 3.3 shows that the upper aquifer is losing water to the deeper aquifer in the Limburg part of the RVG (1- 2 $Mm^3\ yr^{-1}$ depending on the scenario) and the Brabant part of the RVG (64 $Mm^3\ yr^{-1}$ for the most realistic scenario, Figure 3.3a).

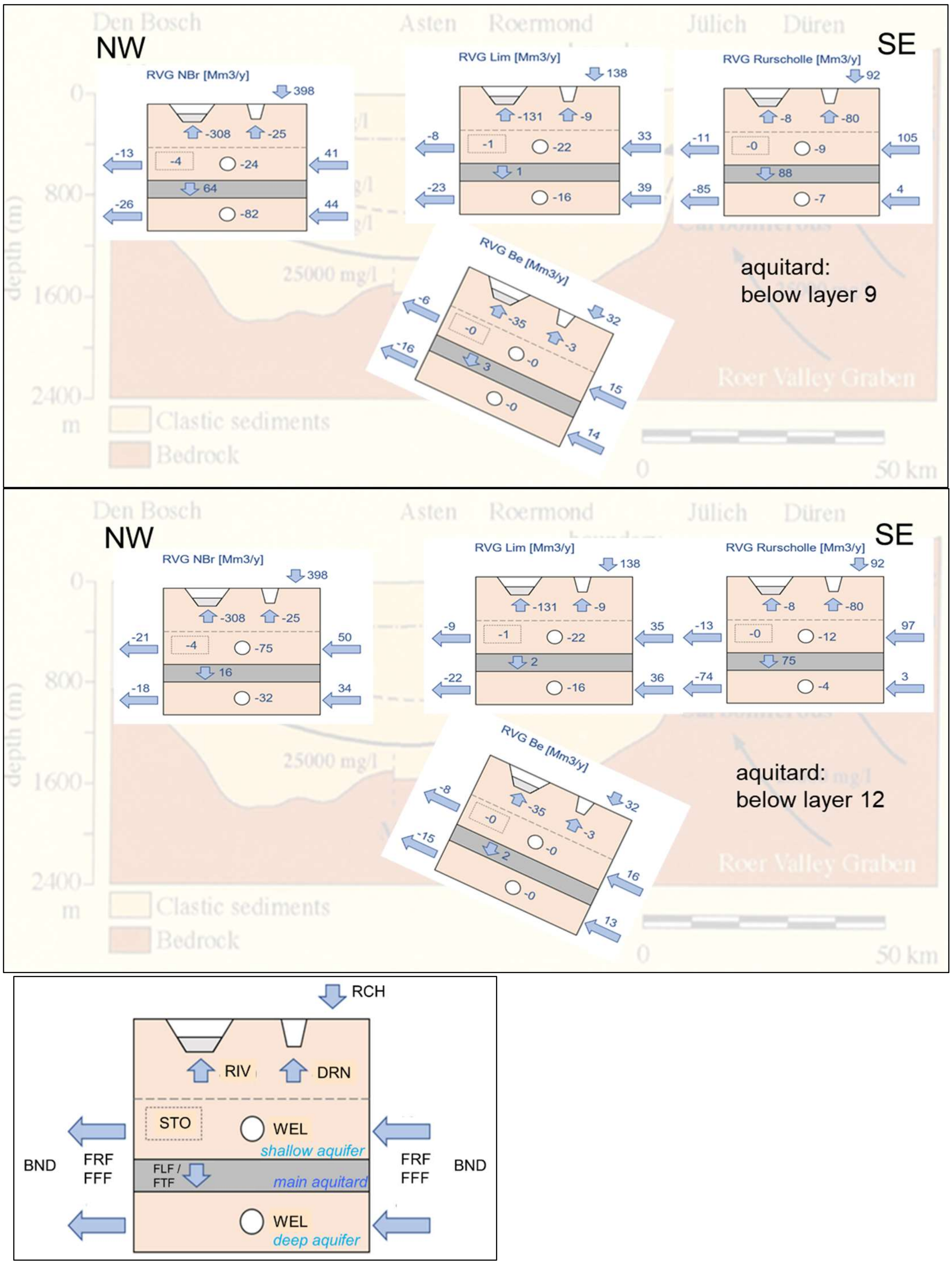


Figure 3.3. Water balances in the main RVG zones, in millions of m3 per year, superposed on the natural situation as depicted by Stuurman et al. 2004. Above (a): main aquitard positioned below model layer 9, relevant for Noord-Brabant. Middle (b): main aquitard positioned below model layer 12, relevant for other zones. Below (c): legend, identical to Figure 2.4.

The same phenomenon of recharge of the deep aquifer from the shallow aquifer is visualised in a different way in *Figure 3.4*. The figure shows the vertical fluxes across the main aquitards in mm/day. Recharge from the shallow aquifer (dominated by Sterksel Formation sands) to the deep aquifer is apparent for the largest part of the RVG in Noord-Brabant, and also apparent for large parts of the RVG in Limburg where recharge is indicated over the Kieseloolite aquitard. The figure shows upward seepage only in the Meuse valley in Limburg and at the downstream end of the RVG, in north-western Noord-Brabant. For the Noord-Brabant part of the RVG, the left figure is most relevant. It shows that the area of upward seepage is limited to ‘s-Hertogenbosch and the area west of it (Langstraat).

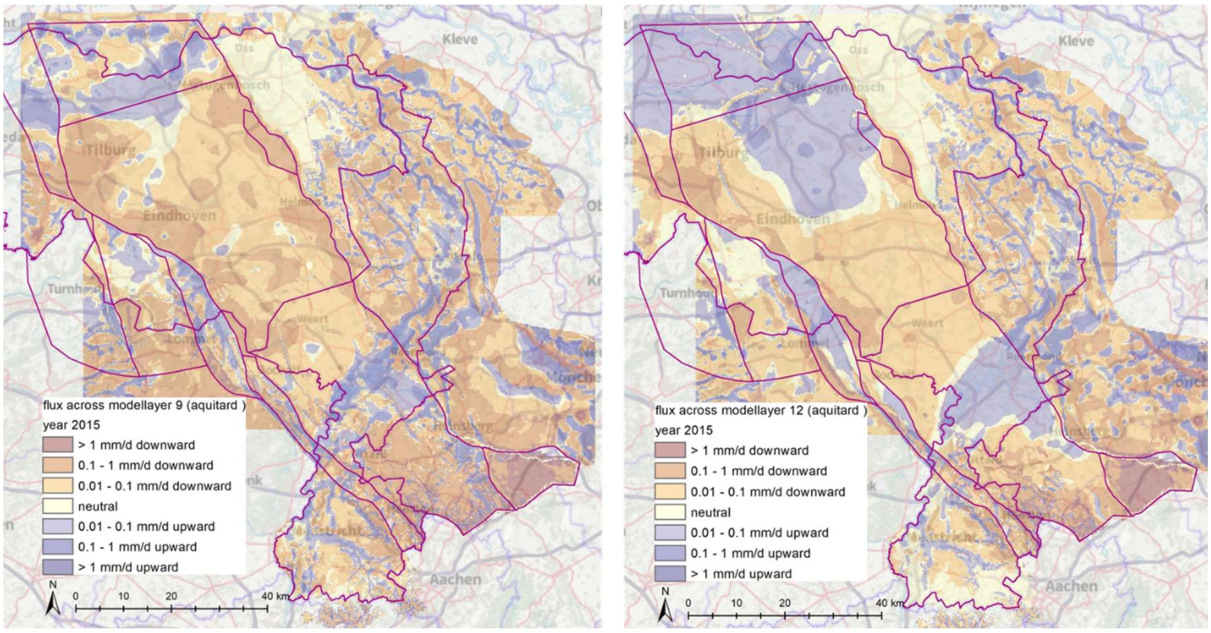


Figure 3.4. Vertical fluxes between shallow and deep aquifer. Left: main aquitard positioned below model layer 9, relevant for Noord-Brabant. Right: main aquitard positioned below model layer 12, relevant for other zones.

3.1.2 *Flow across the fault zones*

For a proper interpretation of the presented fluxes across the Feldbiss and Peelrand faults, the method for quantifying lateral flows across the more complex sections of these faults is outlined below:

- The lateral inflow into the RVG across the Feldbiss fault was quantified by taking the flux across the easternmost fault, directly bordering the RVG, see **Error! Reference source not found.**.
- Likewise, the lateral inflow into the RVG across the Boekel Block in Noord-Brabant, lying in between the main Peelrand Fault and a side fault, was quantified by taking the flux across the side fault, see also **Error! Reference source not found.**.

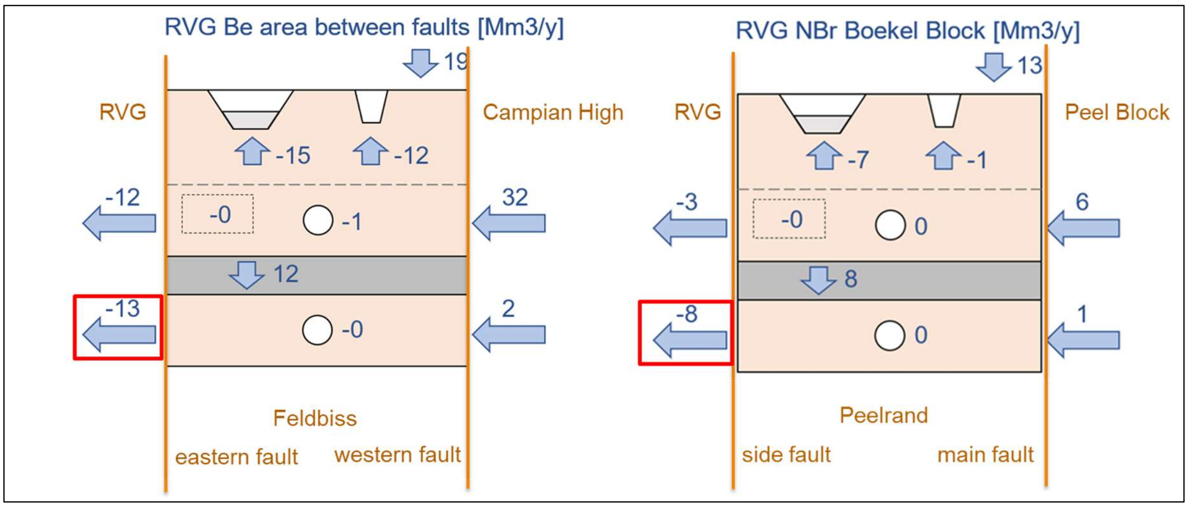
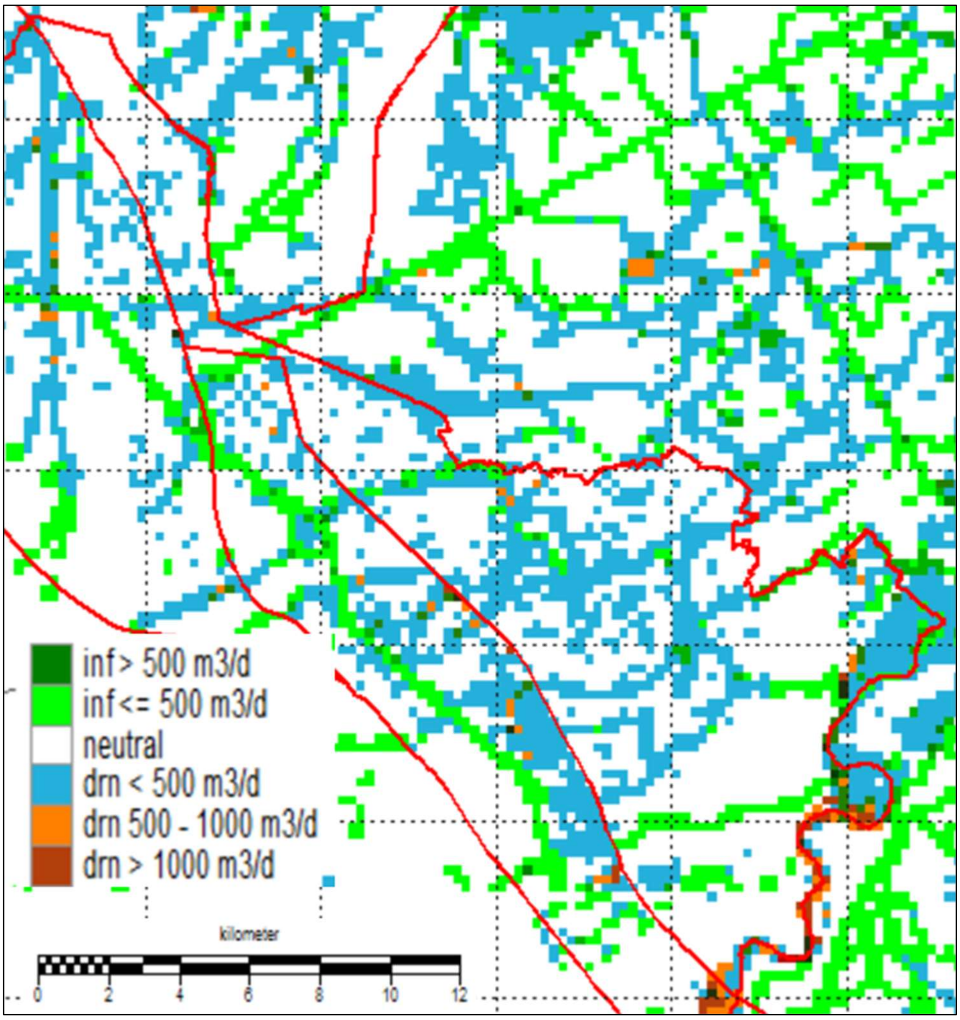


Figure 3.5. Inflow into the RVG across complex fault systems in Mm^3 yr^{-1}. Left: Feldbiss (zone 18). Right: Peelrand Fault (Boekel Block) (zone 27). The fluxes counted as inflow into the deep RVG are boxed red. Main aquitard positioned below model layer 9.

3.1.3 *Drainage fluxes and phreatic storage*

In the shallow aquifer, marked differences in net phreatic recharge are apparent between the RVG-zones. Net phreatic groundwater recharge is defined as precipitation surplus minus drainage of groundwater to the surface water system (**Error! Reference source not found.**). Net phreatic recharge ranges from 37 mm/y in Noord-Brabant to -39 mm/y in Northeast Belgium. These small numbers indicate that on average, the shallow aquifer receives a limited amount of net recharge. It means that little recharge is available for groundwater abstractions if lateral inflow would be zero. The precipitation surpluses in the four zones displayed are similar (201-228 mm yr^{-1}), and therefore the apparent phreatic recharge deficit in Northeast Belgium appears to be related more to a relatively high simulated drainage flux. The drainage flux is contributed to by drainage to the river Meuse, smaller streams like the Itterbeek, and to a lesser extent agricultural drainage (see *Figure 3.6*). It was not further investigated to what extent the underlying cause of the phreatic recharge deficit in this zone is real or related to certain model settings.

Furthermore, it is noted from **Error! Reference source not found.** that the phreatic storage term is on average negative by several mms in all zones except the Rurscholle for the period 2009-2016, which means that effectively water is lost from storage during years that were not exceptionally dry. This storage deficit is expected to have continued,



if not intensified, in the dry years that followed after the water balance period (2009-2016).

Figure 3.6. Drainage fluxes from the Belgian part of the RVG. ''drn'' stands for drainage, ''inf'' stands for infiltration.

3.2 Volumes and fluxes

For each aquifer definition, total volumes of groundwater were quantified per zone, assuming an average aquifer porosity of 30%. The results for the deep aquifer including H3O-units 0252 and 0253 are shown in Figure 3.7 and Figure 3.8 in millions of m^3, together with the recharge from the shallow aquifer, in millions of m^3 per year. The ratio of the recharge from the shallow aquifer to the total water volume in the deep aquifer (recharge-to-volume or R2V-ratio) can be inferred from both figures, and is shown in *Table 3.1*. Note that groundwater in aquitards within the deep aquifer is excluded from the calculated volumes.

The R2V-ratio may be considered as a crude approximator of a groundwater replacement rate in the deep aquifer, assuming that recharge from the shallow aquifer represents younger water, and all other water balance terms in the deep aquifer represent older water.

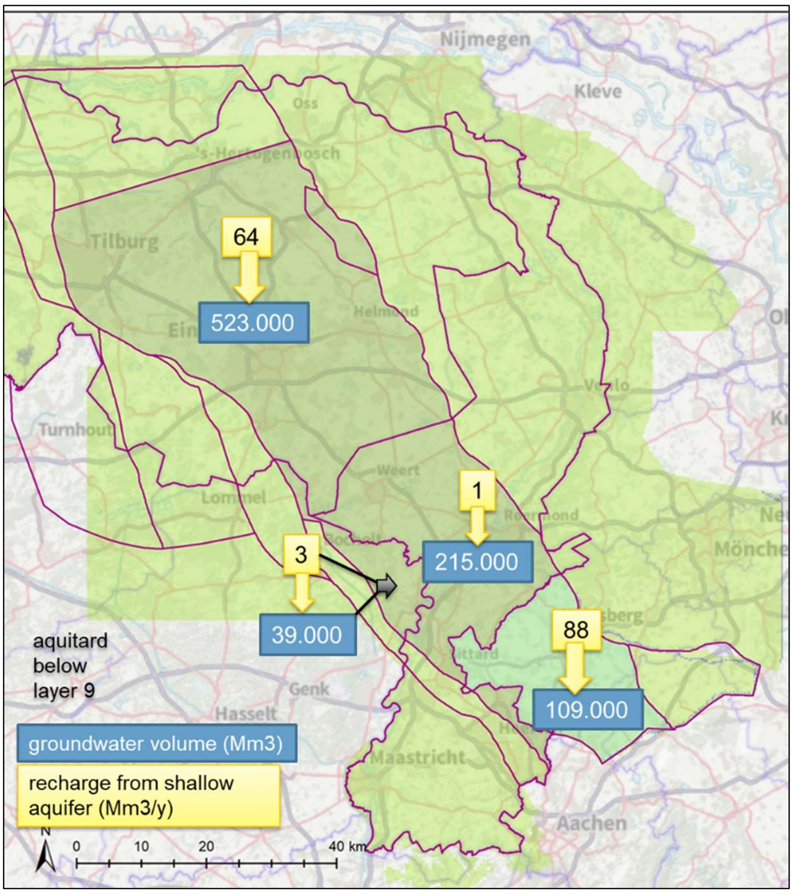


Figure 3.7. Total volumes of groundwater per zone, deep aquifer including H3O-units 0252 and 0253, with main aquitard positioned below model layer 9, relevant for Noord-Brabant. Note: groundwater in aquitards within the deep aquifer is excluded from the presented volumes.

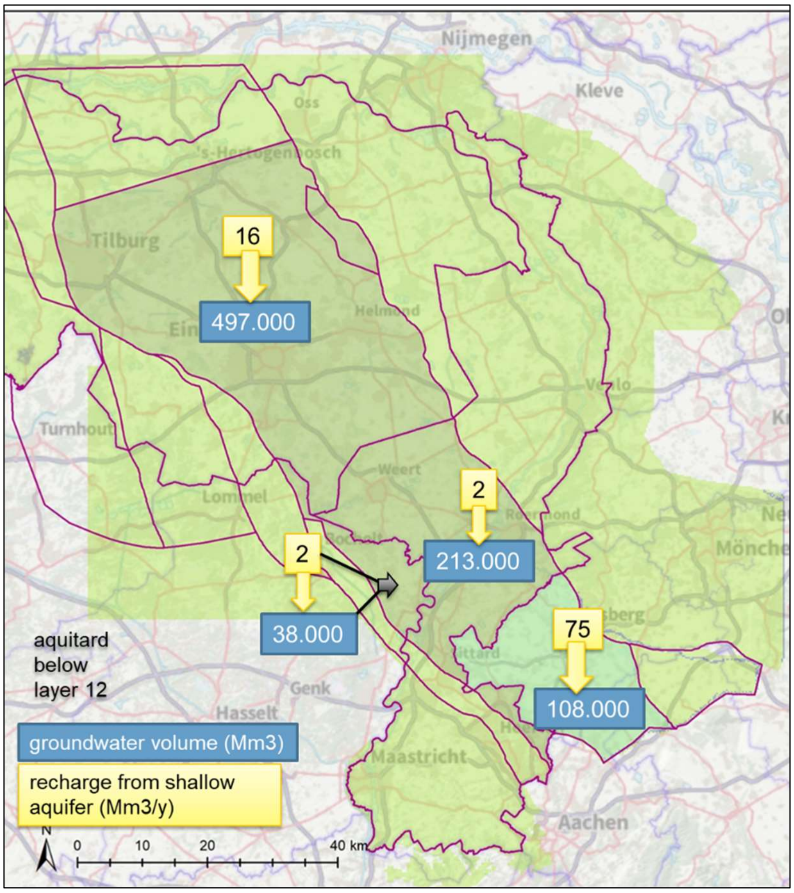


Figure 3.8. Total volumes of groundwater per zone, deep aquifer including H3O-units 0252 and 0253, with main aquitard positioned below model layer 12, relevant for other zones. Note: groundwater in aquitards within the deep aquifer is excluded from the presented volumes.

Table 3.1. Ratio of recharge flux to total volume (R2V), deep aquifer including H3O-units 0252 and 0253. The less relevant figures (due to main aquitard position) are greyed out.

Zone	R2V ratio deep aquifer incl. 0252/0253 main aquitard below model layer 9	R2V ratio deep aquifer incl. 0252/0253 main aquitard below model layer 12
Noord-Brabant RVG	0,01 % (per year)	0,003 % (per year)
Central Limburg NL RVG	0,0003 % (per year)	0,001 % (per year)
Northeast Belgium RVG	0,007 % (per year)	0,005 % (per year)
Rurscholle	0,08 % (per year)	0,07% (per year)

The figures shown in Figure 3.7, *Figure 3.7* and *Table 3.1* apply to the deep aquifer with the geohydrological basis as implemented in IBRAHYM-ROERDAL, i.e. including H3O-units 0252 and 0253 (Breda or Diest/Bolderberg/Ville Formation). To illustrate the complications provoked by different implementations of the concept of geohydrological basis, as described earlier in section 2.1.2, an attempt was also made to quantify groundwater volumes in the deep aquifer considering the top of these H3O-units as geohydrological basis. This attempt is illustrated for the Dutch part of the RVG, where the shallow aquifer is part of the WFD Groundwater Body Maas Sand, and the deeper aquifer is known as the Maas Slenk Diep groundwater body. This approach to quantification of groundwater volumes is not straightforward, because the geohydrological basis according to this implementation is not represented by one single model layer. Groundwater volumes in the Dutch part of the RVG (zones 13 and 15) were therefore estimated from two alternative information sources: (1) the fact sheet of WFD groundwater body Maas Slenk Diep (Provincie Noord-Brabant, 2015), and (2) a draft version of the map of estimated groundwater storage that was constructed for RESOURCE WP 6 (Pan-EU Groundwater Resources Map, see *Figure 3.9*).

- The volume of Maas Slenk Diep reported on the WFD fact sheet is 179 km^3, but this also includes the northern Campian block around Tilburg and the polder area north of ‘s-Hertogenbosch and therefore is larger than the volume for zones 13 and 15 only. Furthermore, it appears that the volume of aquitards *within* Maas Slenk Diep are also counted for the volume, but this supposition could so far not be verified;
- The groundwater volume in the RVG, zones 13 and 15, was visually estimated from *Figure 3.9* to be 126 km^3. This volume excludes aquitards and brackish groundwater volumes, but it does include shallow aquifers. The volumes of the shallow aquifers in zones 13 and 15 were calculated as described in section 2.2.6 and are 42 km^3 (with main aquitard below model layer 9) and 70 km^3 (with main aquitard below model layer 12). Consequently, the groundwater volume in Maas Slenk Diep, as estimated from this information, lies somewhere between 56 and 84 km^3. It must be noted that the cell size on the Pan-EU map is 10 x 10 km^2 which introduces uncertainty.

In the quantification including H3O-units 0252 and 0253, the groundwater volume for zones 13 and 15 together is 738.000 or 710.000 m^3 (depending on main aquitard position; see *Figure 3.7*). Using the alternative information and taking into account the associated uncertainties, the total fresh groundwater volume in WFD Maas Slenk Diep in zones 13 and 15 is roughly estimated to be 1/7 of this amount. This would lead to a 7-fold increase in R2V-ratios in zones 13 and 15.

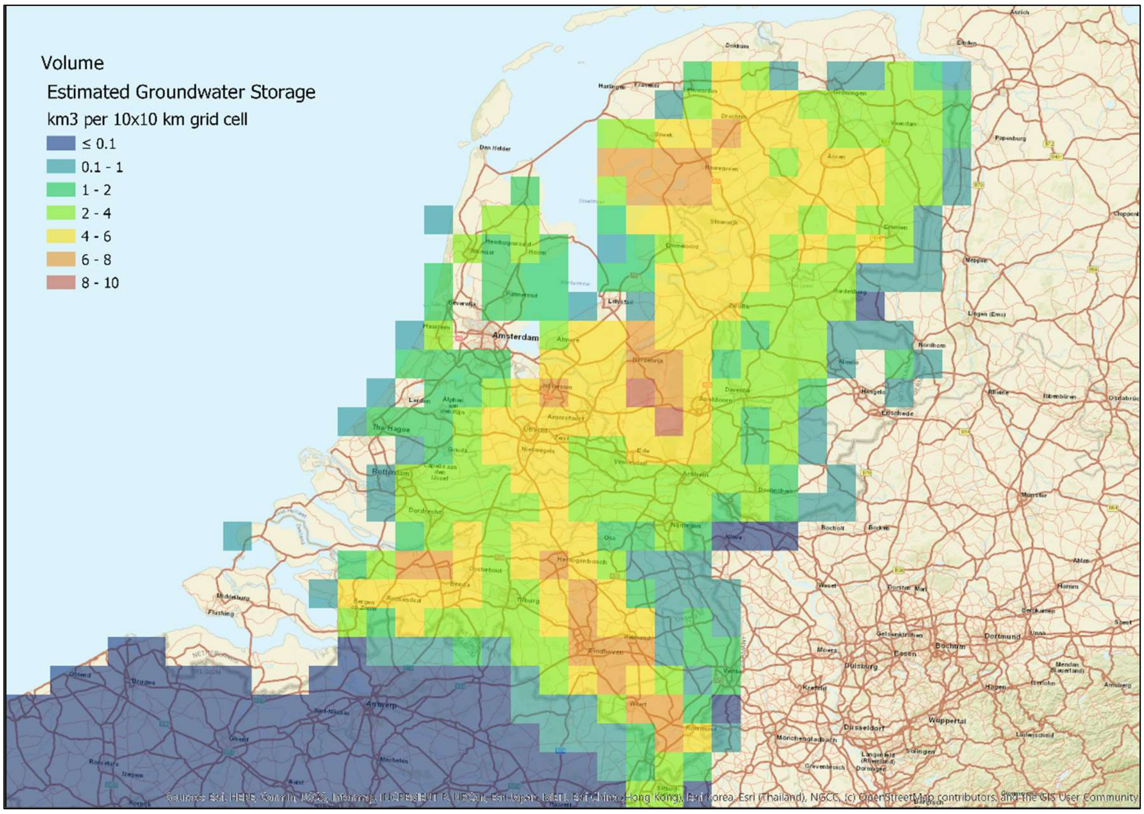


Figure 3.9. Estimated groundwater storage, detail of the Pan-EU Groundwater Resources Map (RESOURCE WP6, draft version). Note: the volume shown also includes shallow aquifers.

Table 3.2. Ratio of recharge flux to total volume (R2V), deep aquifer, excluding H3O-units 0252 and 0253 and brackish groundwater. The less relevant figures (due to main aquitard positioning) are greyed out.

Zone	R2V ratio deep aquifer excl. 0252/0253 model layer 9 = aquitard	R2V ratio deep aquifer excl. 0252/0253 model layer 12 = aquitard
Noord-Brabant RVG	0,09 % (per year)	0,02 % (per year)
Central Limburg NL RVG	0,002 % (per year)	0,006 % (per year)
Northeast Belgium RVG	not determined	not determined
Rurscholle	not determined	not determined

Whatever definition is adopted for the deep aquifer, according to *Table 3.1* and *Table 3.2* the R2V-ratios vary over almost two orders of magnitude between the zones considered. The high ratio in the Rurscholle is explained by the large recharge flux in this zone. It may be argued that because of its upstream location, deep groundwater in the Rurscholle is relatively young, and the concept of groundwater replacement may have less practical significance. The low R2V-ratio in Central Limburg NL is explained by the limited areal extent over which recharge occurs. Below the Meuse valley, the seepage is upward from the deep aquifer, instead (see also *Figure 3.4*).

The R2V-ratio is inversely related to the so-called turnover time. Hence, if the R2V-ratio is 0.1% per year, turnover time is 1000 years. According to an exponential relation between turnover time and groundwater replacement proposed by Vogel (1967) and later referenced by Van Ommen (1986), it would then take ~3000 years to arrive at 95% replacement of all groundwater, assuming an ideally mixed reservoir.

It should be noted that the absolute values in *Table 3.1* and *Table 3.2* are quite uncertain, due not only to the crude estimation of the deep aquifer volumes, but also due to the applied assumptions and other uncertainties which will be further addressed in section 3.3.

3.3 Uncertainties

3.3.1 General

The results presented in sections 3.1 and 3.2 are subject to a number of sources of uncertainty, which will be discussed hereafter.

Groundwater abstraction for agricultural irrigation is not represented in the Dutch part of the RVG. This water balance term is estimated to be in the order of magnitude of 10^7 to 10^8 m^3/y (Verhagen et al., 2019). The depth of abstraction is not registered in the permit and is thus formally not known. According to Verhagen et al. (2019), groundwater abstraction for agricultural irrigation occurs mainly from the shallow aquifer in the RVG. If this is the case, then the omission of this term from the water balance may lead to an overestimation of recharge from the shallow to the deep aquifer, and hence to an overestimation of the R2V-ratios shown in *Table 3.1* and *Table 3.2*. Conversely, if (occasional) abstractions take place from the deep aquifer, then the effect on the R2V-ratios may be opposite.

The presented R2V-ratios for the RVG deep aquifer do not take into account upconing of still deeper groundwater. Despite its still older age, this groundwater may be brackish and therefore influence the potential for use of the RVG deep aquifer. Furthermore, the vertical position of the fresh-brackish groundwater interface is not well known in large parts of the RVG, in particular in the southeast.

In addition to addressing general features, insight in uncertainties can be gained by comparisons with other groundwater models in the same area and for the same period. The Brabant model and MS model proved most suitable for comparisons; see sections 3.3.2 and 3.3.3. respectively.

Vermeulen & Op den Kelder (2020) used information from the RWE model to establish model input to IBRAHYM-ROERDAL in the German part of the modelling area. The information concerned hydraulic heads as a fixed (Dirichlet) boundary condition on IBRAHYMs southeastern boundary, and hydraulic permeabilities. Adjustments to both types of information were made and motivated for the implementation to IBRAHYM-ROERDAL. In addition, several comparisons of the results of both models are reported in Vermeulen & Op den Kelder (2020). Therefore, a comparison between IBRAHYM-ROERDAL and the RWE Power model was not considered for the present analysis.

3.3.2 Comparisons with Brabant model

The Brabant model is the regional groundwater model for the province of Noord-Brabant. Water balances simulated with the Brabant model are available for the Noord-Brabant part of the RVG for the period 2009-2016 (Verhagen et al., 2019). The water balances are based on a lateral zonation almost identical to the zonation applied in the present analysis. In the reported water balance of the Brabant model, abstractions for agricultural irrigation were left out, making it suitable for a comparison with the water balance terms presented in section 3.1 of this report. For this comparison, a different aquifer definition was imposed on the water balance generation from IBRAHYM-ROERDAL. To line up the aquifer definitions of both models and obtain optimal agreement between abstraction amounts in both models, the main aquitard was positioned below IBRAHYM-ROERDAL model layer 6 and above layer 7, representing H3O-unit SY-k-1. The comparison is visualised in **Error! Reference source not found.**.

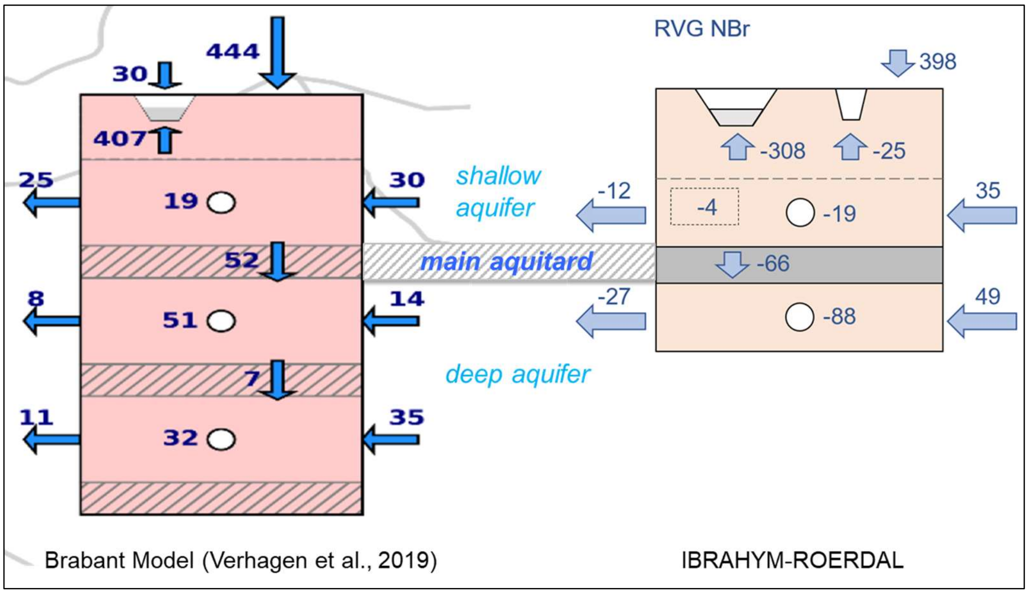


Figure 3.10. Comparison of water balance terms, in millions of m3 per year, 2009-2016. Main aquitard below IBRAHYM-ROERDAL model layer 6, H3O-unit SY-k-1.

Groundwater abstraction from the shallow aquifer is identical in both models, as is the lateral inflow into the deep aquifer. Likewise, net phreatic recharge is almost identical in both models (444+30-407=67 Mm^3 yr^{-1} in the Brabant model and 398-308-25=65 Mm^3/y in IBRAHYM-ROERDAL. Finally, also the sums of recharge to the deep aquifer and lateral outflow from the shallow aquifer are almost equal in both models: 25 + 52 = 77 Mm^3/y in the Brabant model and 12 + 66 = 78 Mm3/y in IBRAHYM-ROERDAL. The different contributions of both terms may be explained by different hydraulic permeabilities. It is known that the initial vertical permeabilities of the Brabant model layers representing H3O-units WA-k-1 and SY-k-1 in the RVG were decreased by factors

10-25 and 5 (respectively) during calibration (Verhagen et al., 2019). The resulting higher hydraulic resistances of these aquitards in the Brabant model may explain the higher portion of lateral outflow from the shallow aquifer and the lower portion recharging the deep aquifer. It is noted however, that an explicit comparison of hydraulic resistances in both models was not made.

The difference in groundwater abstraction from the deep aquifer may be caused by a slightly different location of the boundary between RVG-zones 12 and 15, leading to the allocation of groundwater abstractions to different zones in both models.

In the current aquifer definition with model layer 6 as main aquitard, the total lateral inflow into the shallow aquifer in IBRAHYM-ROERDAL is 35 Mm^3/y of which 5 Mm^3/y flows in from upstream RVG, 16 Mm^3/y over the Feldbiss fault and 14 Mm^3/y over the Peelrand fault. The total lateral inflow in the Brabant model cannot be decomposed with the available information, but an additional analysis with the Brabant model suggests that the average inflow (2009-2016) over the Peelrand fault into the shallow aquifer is about 68,000 m^3 per year (pers. comm. T. van Steijn, Brabant Water). This is two orders of magnitude lower than in IBRAHYM-ROERDAL. The relatively high flux over the Peelrand fault in IBRAHYM-ROERDAL may be related to the apparent absence of fault resistances in model layers 1 and 2, while in the Brabant model a fault resistance of 10,000 days is applied over the entire depth. The impact of the uncertainty of the shallow Peelrand Fault resistance on water balance terms and R2V-ratios in the deep aquifer may be limited due to the high resistances of the main aquitards, but this supposition was not further verified.

3.3.3 Comparison with MS model

De Smedt et al. (2007) provide information about water balance terms simulated with the MS model for the year 2000, for the total MS model area as well as the Belgian part of it. Both areas, however, extend beyond the southwestern boundary of IBRAHYM-ROERDAL. This limits possibilities to line up MS model and IBRAHYM-ROERDAL water balance information. A comparison is further complicated by the apparently[2] stationary nature of the MS model results, as opposed to the transient nature of the IBRAHYM-ROERDAL output. Therefore, the comparison with the MS model was limited to two water balance terms that could be unambiguously quantified for the area to the north east of the Feldbiss fault (i.e. RVG Northeast Belgium, zone 16). More specifically, Figure 6.16 and Table 6.20 in De Smedt et al. (2007) were used to quantify (1) the lateral inflow

[2] It could not directly be inferred from the report whether the simulations were stationary or transient. Stationarity is assumed because often averages are addressed in the text, and no reference is made to phreatic storage terms in the water balances.

into the deep aquifer, and (2) the recharge from the shallow to the deep aquifer[3]. The main aquitard separating the shallow and deep aquifer is positioned below model layer 13 and above layer 14 in IBRAHYM-ROERDAL, representing H3O-unit Kl-k-2 and denoted as HCOV-0212 in DeSmedt et al. (2007). The comparison is shown in *Figure 3.11*.

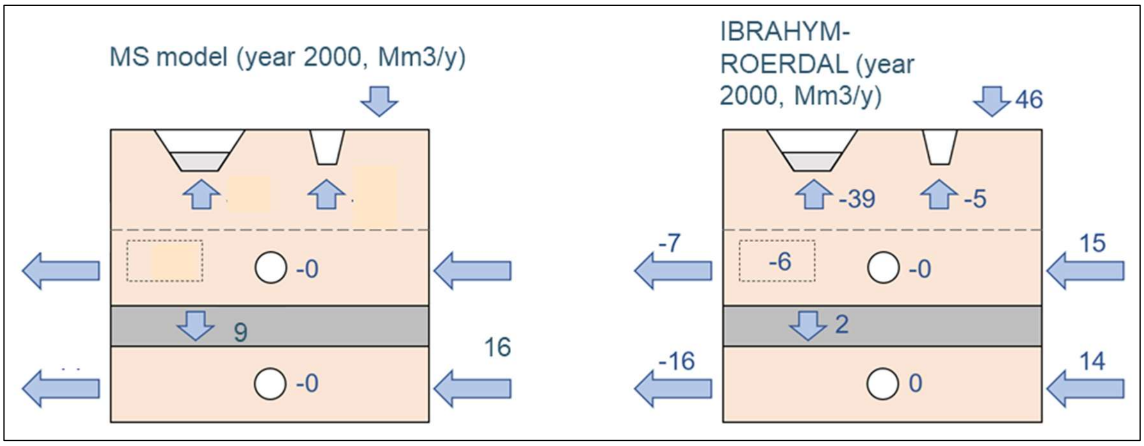


Figure 3.11. Comparison of selected water balance terms, in millions of m3 per year. Left: MS model, right: IBRAHYM-ROERDAL. Main aquitard: IBRAHYM model layer 13, H3O-unit Kl-k-2.

The lateral inflow into the deep aquifer is similar but not identical in both figures (16 Mm^3/y in the MS model versus 14 Mm^3/y in IBRAHYM-ROERDAL). This may be explained by high, but not identical Feldbiss fault resistances and geometries in both models (a conductivity / width ratio of zero in the MS model[4] versus a resistance of 10,000 days for all deep aquifers in IBRAHYM-ROERDAL). A more pronounced difference is observed for the recharge to the deep aquifer. This may be explained by a negative storage term present in IBRAHYM-ROERDAL, but not in the MS model. It appears that in the transient IBRAHYM-ROERDAL simulation, hydraulic heads in the year 2000 are in a recession limb following peak values in the preceding wet years.

In addition, a semi-quantitative comparison was made for the drainage flux to rivers and streams. A map of IBRAHYM-ROERDAL fluxes to rivers and streams in the year 2000 was made with a legend identical to Figure 6.17 in DeSmedt et al. (2007). The comparison of both maps is shown in *Figure 3.12*. Along the Feldbiss fault, the identical infiltration classes for the main canals (Zuid-Willemsvaart and Kanaal Bocholt-Herentals) are evident, as well as almost identical drainage patterns in the streams running to the north east into the RVG. Southwest of the Feldbiss fault zone, drainage prevails in the MS model while infiltration dominates in IBRAHYM-ROERDAL. The causes of this

[3] In Figure 6.16, the inflow across the Feldbiss into and below HCOV-0212 is 7%, and the recharge from the shallow to the deep aquifer (through HCOV-0212) is 4%. Considering 1% being 6078.62 m^3/d according to Table 6.20 in De Smedt et al. (2007), these percentages correspond to 15.5 Mm^3/y and 8.9 Mm^3/y, respectively.

[4] Source: Severyns & De Smedt (2006), p60).

evident difference were not further investigated because the area lies relatively far from the RVG.

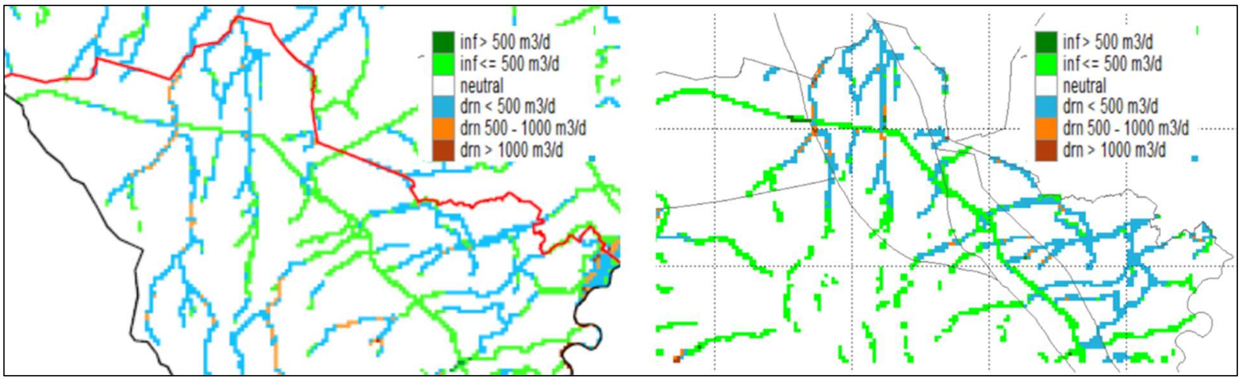


Figure 3.12. Semi-quantitative comparison of fluxes to rivers and streams, in m3 per day. Left: MS model, right: IBRAHYM-ROERDAL. Note: the blue-coloured drainage area along the river Meuse, visible for the MS model only, is represented in a part of the river drainage output package in IBRAHYM-ROERDAL that was not made visible, to maintain readability.

4 CONCLUSIONS

A cross-border analysis of water balances, fluxes and groundwater volumes in the Roer Valley Graben (RVG) was carried out, based on simulation output of the groundwater model IBRAHYM-ROERDAL. The analysis comprised the years 2009 through 2016. Water balance terms were quantified for 27 zones in and adjacent to the RVG. Focus of the analysis was on the four zones that comprise the major part of the RVG: Noord-Brabant excluding the polder area, Central Limburg NL, Northeast Belgium and Rurscholle. The analysis was performed for aggregated model layers composing the shallow RVG aquifer and the deep RVG aquifer. This resulted in multiple sets of results, according to different positions of the main aquitards separating both aquifers.

The Rurscholle may be regarded as the source area of the RVG deep aquifer. Further downstream, the NW directed groundwater flux decreases, despite lateral inflow from the sides across the boundary faults of the graben. Total water balances and vertical flux maps show that groundwater abstractions are the dominant fluxes. Furthermore, seepage on average is downward in large portions of the RVG, implying that recharge of the deep aquifer from the shallow aquifer occurs. A comparison with older studies points towards a reversal of the vertical flow directions between the upper and deeper aquifers over large parts of the RVG.

In the shallow RVG aquifer, marked differences in net phreatic recharge are apparent between the RVG-zones. Furthermore, the phreatic storage term is on average negative by several mms over the eight years considered in all RVG-zones except the Rurscholle. This suggests a slow loss of stored groundwater over time, which may have increased after the recent dry years.

Crude approximations of the replacement rate of groundwater in the deep aquifer were made using the recharge-to-volume (R2V-) ratio based on the analysed water balance terms. Recharge here is represented by the vertical flux through the main aquitard covering the deep aquifer. Calculated R2V-ratios range from 0,001% to 0.1 % (per year), but depend greatly on the definition of the RVG deep aquifer: including or excluding the deep, marine and partly brackish H3O-units 0252 and 0253 (a.k.a. Breda or Diest/Bolderberg/Ville-Formation).

The R2V-ratio is inversely related to the so-called turnover time. Hence, if the R2V-ratio is 0.1% per year, turnover time is 1000 years. It would then take ~3000 years to arrive at 95% replacement of all groundwater, assuming an ideally mixed reservoir.

The absence of groundwater abstractions for agricultural irrigation, uncertainties around fault resistances and the vertical position of the fresh-brackish groundwater interface, and uncertainties related to estimated groundwater volume are suspected to have significant impact on the uncertainty of the analysis conducted. The latter uncertainties relate to different implementations of the geohydrological basis. For some groundwater management purposes, e.g. aimed at compliance to the European Water Framework Directive (WFD), the most appropriate geohydrological basis is not represented by one single IBRAHYM-ROERDAL model layer.

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6 REFERENCES

Deckers, J., R. Vernes, W. Dabekaussen, M. den Dulk, H. Doornenbal, M. Dusar, J. Hummelman, J. Matthijs, A. Menkovic, R. Reindersma, J. Walstra, W. Westerhoff & N. Witmans, 2014. Geologisch en hydrogeologisch 3D model van het Cenozoïcum van de Roerdalslenk in Zuidoost-Nederland en Vlaanderen (H3O – Roerdalslenk). H3O-report 2014/ETE/R/1 / TNO 2014 R10799.

De Smedt, F., B. Verbeiren & G. Adem, 2007-1. Ontwikkeling van regionale modellen ten behoeve van het Vlaams grondwater model (VGM) in GMS/MODFLOW. Perceel 1: Centraal Kempisch Systeem. Deelrapport 3: Beschrijving modelresultaten referentietoestand 2000 en scenario's. Report Vrije Universiteit Brussel (VUB) for AMINAL – Dept. of Water, file L 2003 S 0013 X.

De Smedt, F., J. Severyns & G. Adem, 2007-2. Ontwikkeling van regionale modellen ten behoeve van het Vlaams grondwater model (VGM) in GMS/MODFLOW. Perceel 2: Maassysteem. Deelrapport 3: Beschrijving modelresultaten referentietoestand 2000 en scenario's. Report Vrije Universiteit Brussel (VUB) for AMINAL – Dept. of Water, file L 2003 S 0013 X.

McDonald, M.G. & A.W. Harbaugh, 1988. A modular three-dimensional finite-difference ground-water flow model. Techniques of Water-Resources Investigations, Book 6. U.S. Geological Survey.

Ommen, H. C. van, 1986. Influence of diffuse sources of contamination on the quality of outflowing groundwater including non-equilibrium adsorption and decomposition, Journal of Hydrology, 88, 79–95.

Provincie Noord-Brabant, 2015. Fact sheet Maas Slenk Diep, KRW fact sheet NLGW0018, 02-02-2015, downloaded from www.brabant.nl on 30-03-2021.

RWE Power AG, 2013. Bericht Grundwassermodell für das Rheinische Braunkohlenrevier, Sammelbescheid zur Neugestaltung bzw. Optimierung des wasserwirtschaftlichen Berichtswesens im Rheinischen Braunkohlenrevier vom 16.10.2003 [86.42.63-2000-1], Bericht 5.5: Fortschreibung der Grundwassermodelle, Cologne, 31. October 2013.

Severyns, J. & F. De Smedt, 2006. Ontwikkeling van regionale modellen ten behoeve van het Vlaams grondwater model (VGM) in GMS/MODFLOW. Perceel 2: Maassysteem. Deelrapport 2: Opbouw van het grondwaterstromingsmodel, gevoeligheidsanalyse en calibratie. Report Vrije Universiteit Brussel (VUB) for AMINAL – Dept. of Water, file L 2003 S 0013 X.

Stuurman, R.J., 2004. Een verkenning naar de interactie tussen diep, paleogeen grondwater en ondiep grondwater in de provincie Noord-Brabant. TNO report NITG 04-222-B0909.

Verhagen, F., T. van Steijn, J. Hunink (Deltares) & R. Stuurman (Deltares), 2017. Draagkracht grondwater Noord-Brabant. Report BF3125, RoyalHaskoningDHV.

Verhagen, F., T. van Steijn, B. van der Wal, W. Swiertsra & H. Vermue, 2019. Update Hydrologische Gereedschapskist Noord-Brabant. Report BF3823WATRP1902061020WM, RoyalHaskoningDHV.

Vermeulen, P., F. Roelofsen & A. Veldhuizen, 2015. Actualisatie en Kalibratie IBRAHYM. Beschrijving van activiteiten t.b.v. IBRAHYM v2.0. Report 1206858-000-BGS-0022, Deltares.

Vermeulen, P.T.M., F.J. Roelofsen, B. Minnema, L.M.T. Burgering, J. Verkaik & D. Rakotonirina, 2019. iMod 5.0 User Manual. Deltares.

Vermeulen, P. & T. Op den Kelder, 2020. The impact of Groundwater Extractions in the Roer Valley Graben. Report 1204053-002-BGS-0001, Deltares.

Vogel, J. C., 1967. Investigations of groundwater flow with radiocarbon. Isotopes in Hydrology, pp. 355-368, Int. At. Energy Agency, Vienna.

Zuurdeeg, B.W., Y.M.A. Coenegracht & P.F.M. Van Gaans, 1989. Geothermische Reserves Centrale Slenk, Nederland. Geochemische aspecten van formatiewater. TNO-report OS 89-20.