GeoERA RESOURCE GROUNDWATER

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

Deliverable 3.7

Introducing the GeoERA Groundwater Viewer: analysing groundwater depletion signals in the Roer Valley Graben

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1 INTRODUCTION

The cross-border demonstration project H3O-PLUS aims 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 has been developed in a series of so called 'H3O' projects 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 (see Figure 1.1). H3O-PLUS aims to add attribute data to these maps to facilitate the use of the maps in decision making processes.

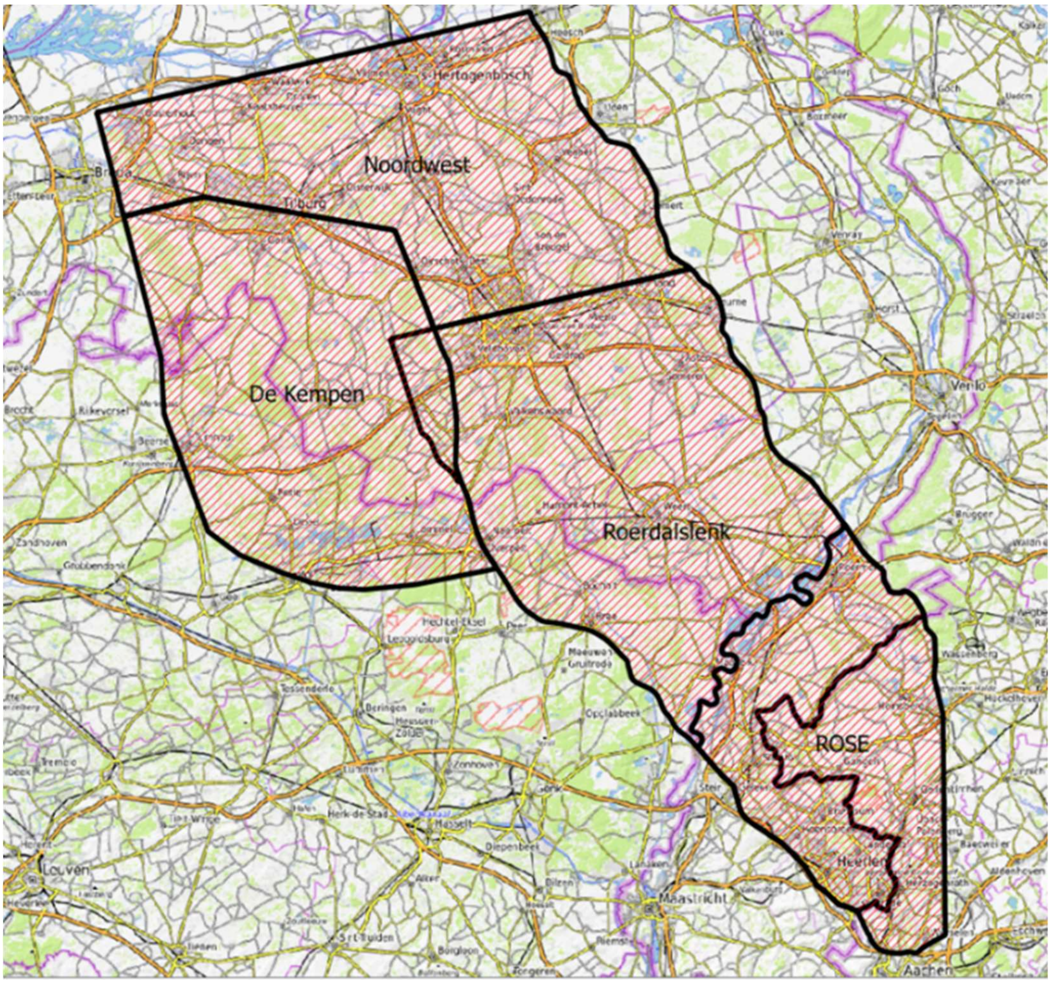

Figure 1.1 Study area of H3O-PLUS project (WP3 of GeoERA Resource) combines the areas of previous H3O projects

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. 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 or the top of the Carboniferous deposits.

This report introduces the newest version of the GeoERA Groundwater Viewer. The GeoERA Groundwater Viewer was newly developed within the GeoERA RESOURCE project. The viewer enables cross-country 3D viewing of patterns in groundwater heads time series and will be publicly available. In this report, the newest version of the web viewer is introduced through some examples of data analysis of groundwater depletion analysis in the H3O-PLUS area. GeoERA RESOURCE deliverable 3.5 (Zaadnoordijk et al., 2021) already gave insight in the application of the viewer but the current update adds a new dimension to the trend detection and analysis tool which is briefly described in the current report. As such, deliverable provides further information on trend detection and analysis in the tool and presents some highlights of the groundwater depletion analysis for the Roer Valley Graben that was performed in H3O-PLUS.

2 ACCESS TO THE VIEWER

The GeoERA Groundwater Viewer will be available at the following address from January 15, 2022:

https://www.grondwatertools.nl/gwsinbeeld/geoera

Before January 15, 2022 a temporary version is available on request from hans-peter.broers@tno.nl.

The new update is an expanded version of the viewer that was presented in GeoERA RESOURCE deliverable 3.5 (Zaadnoordijk et al.,2021).

3 APPLICATION OF THE VIEWER FOR GROUNDWATER DEPLETION ANALYSIS

The new cross-border web viewer distinguishes 3 main menus: Dynamics, Trends and Head Difference (Figure 3.1). As compared to the viewer version presented in GeoERA RESOURCE deliverable 3.5 (Zaadnoordijk et al., 2021) options have been added especially to the Trend menu and to the Head Differences menu, which are illustrated in the next sections. Furthermore, the list of parameters in the Dynamics menu has been expanded with average groundwater heads and groundwater head dynamics (Figure 3.1). The sections 3.1 and 3.2 reveal important patterns for groundwater head temporal trends and for head differences between different aquifers in the Roer Valley Graben groundwater system, respectively.

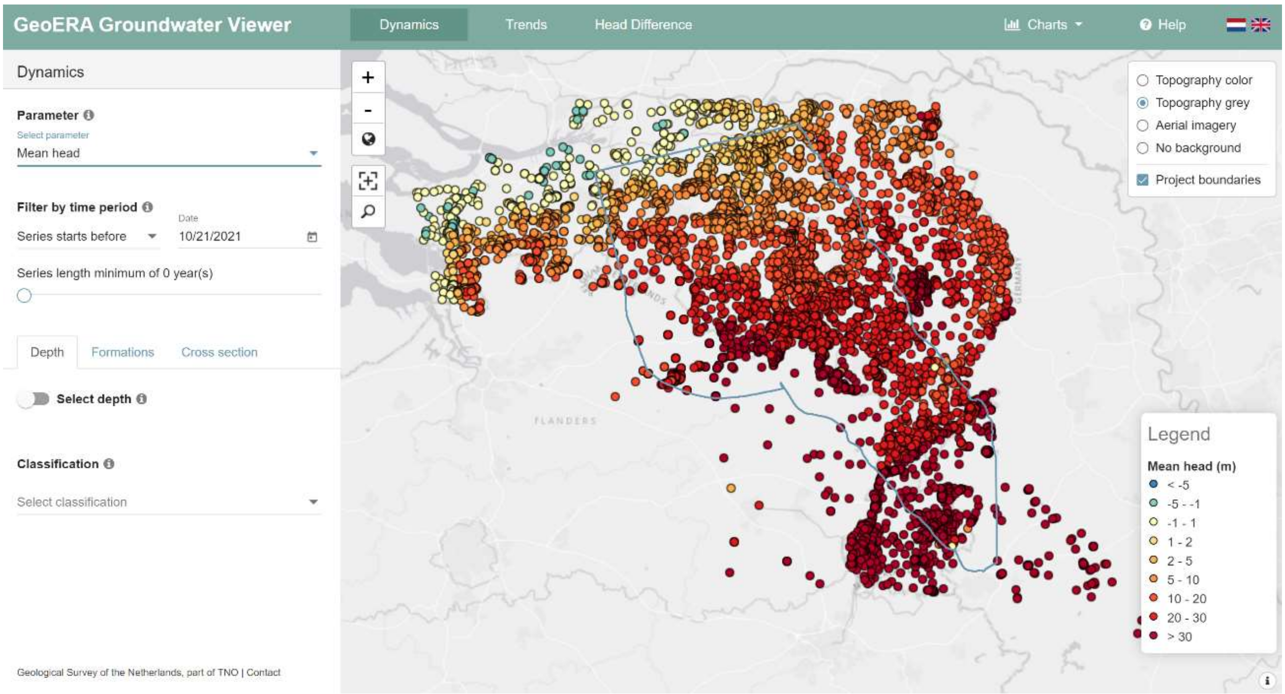

Figure 3.1 GeoERA Groundwater Head Viewer with the three main menus in the centre of the top bar.

3.1 The updated cross-border trend tool

Entering through the Trend menu, the user has three ways to select the time series of the piezometers for which information should be shown:

1. Selecting a depth range under the depth submenu;
2. Selecting one or more geological formations;
3. Selecting a transect for visualizing a hydrogeological cross-section with trend information superposed.

In the updated trend tool, we may now acquire information on aggregated trends for a selected area and the selected depth range, or for the selected area and the selected geological Formations.

3.1.1 Assessing trends for a certain depth range

Figure 3.2 gives the result of a selection of the depth range - 20 m below mean sea level (NAP) plus or minus 20 m for the period 2005-2020, implying that any screen between NAP and NAP -40 m is selected.

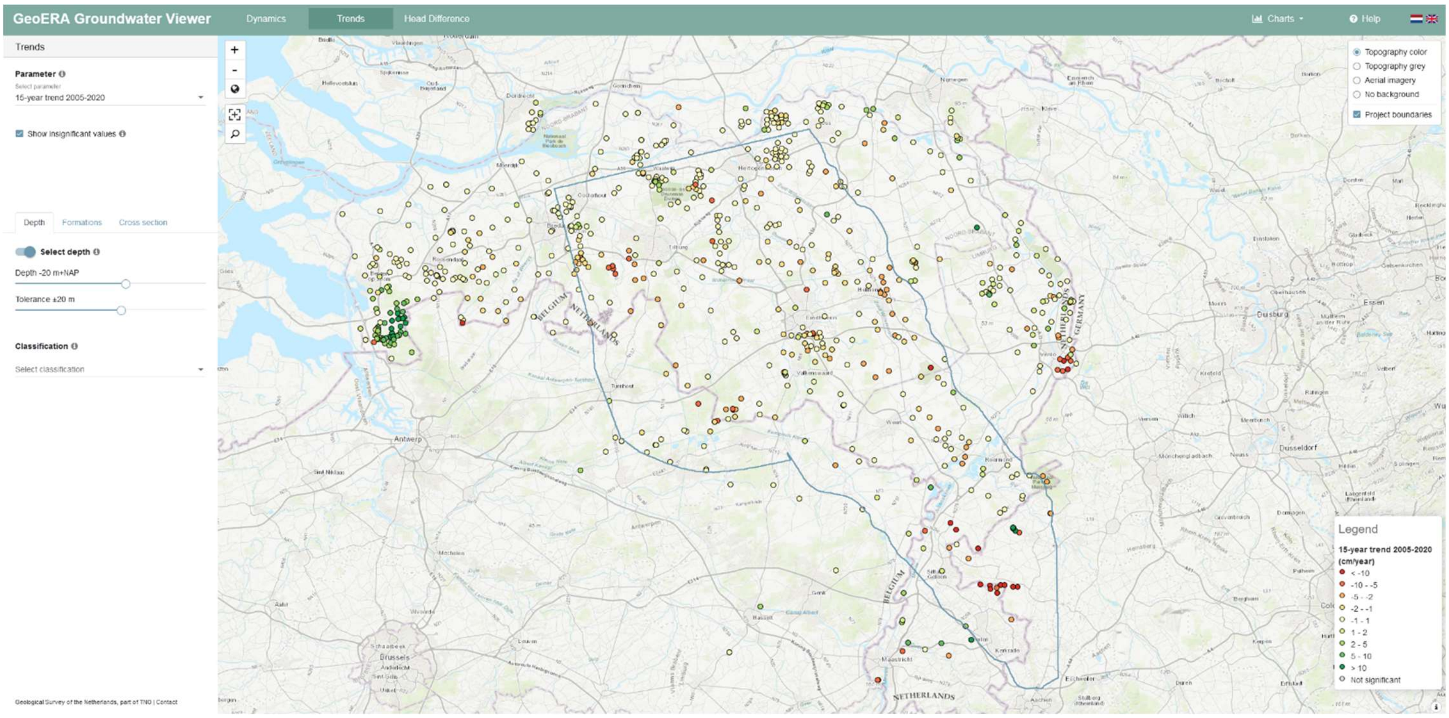

Figure 3.2 Trends for the depth range -20 m NAP (± 20 m) for the period 2005-2020.

Using the map which is shown in Figure 3.2 the user can select a specific observation well for assessing the individual time series at that location (for Dutch locations; information for the Flemish wells can be found in the DOV webtool). An example of such a query is shown in Figure 3.3 for well B60D1027, located near Brunssum in the Dutch province of Limburg. Using the depth interval for selection, the viewer will show the uppermost screen that concurs with the depth interval chosen.

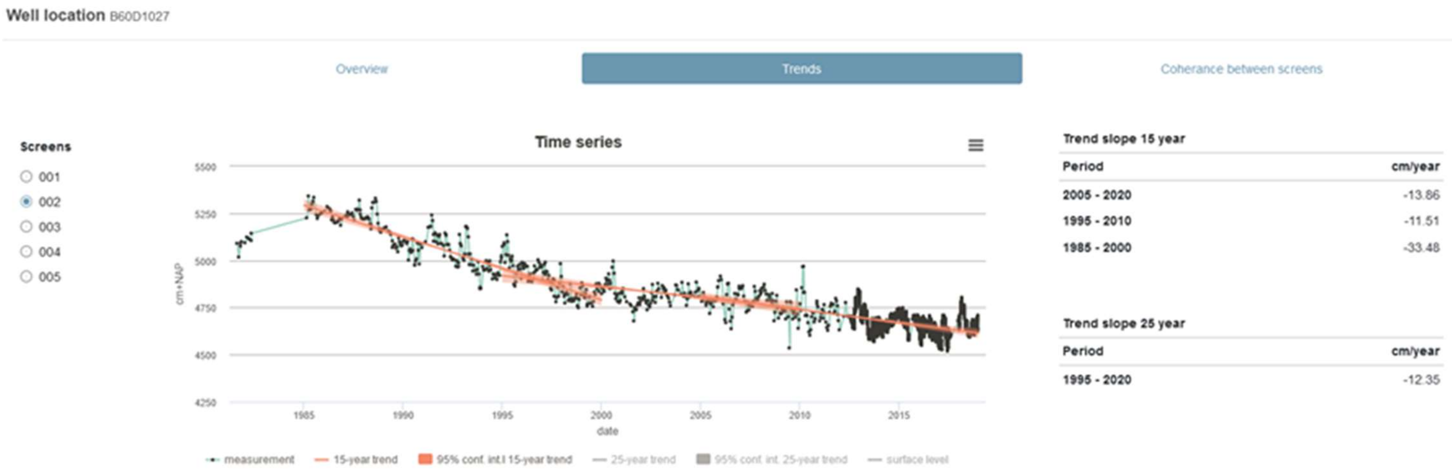

Figure 3.3 Example of the trend tool for observation well B60D1027, screen 2, in the Dutch province of Limburg. Trends are shown for different time segments: 2005-2020, 1995-2010 and 1985-2000. The user may also choose to show the trend over a 25-year period 1995-2020, using the selection buttons below the graph.

3.1.2 Assessing trends for geological Formations

The updated tool can be used to assess temporal groundwater head trends for specific geological formations. We will show some options for illustrating this type of results and start with selecting all wells in the cross-border Kieseloolite Formation.

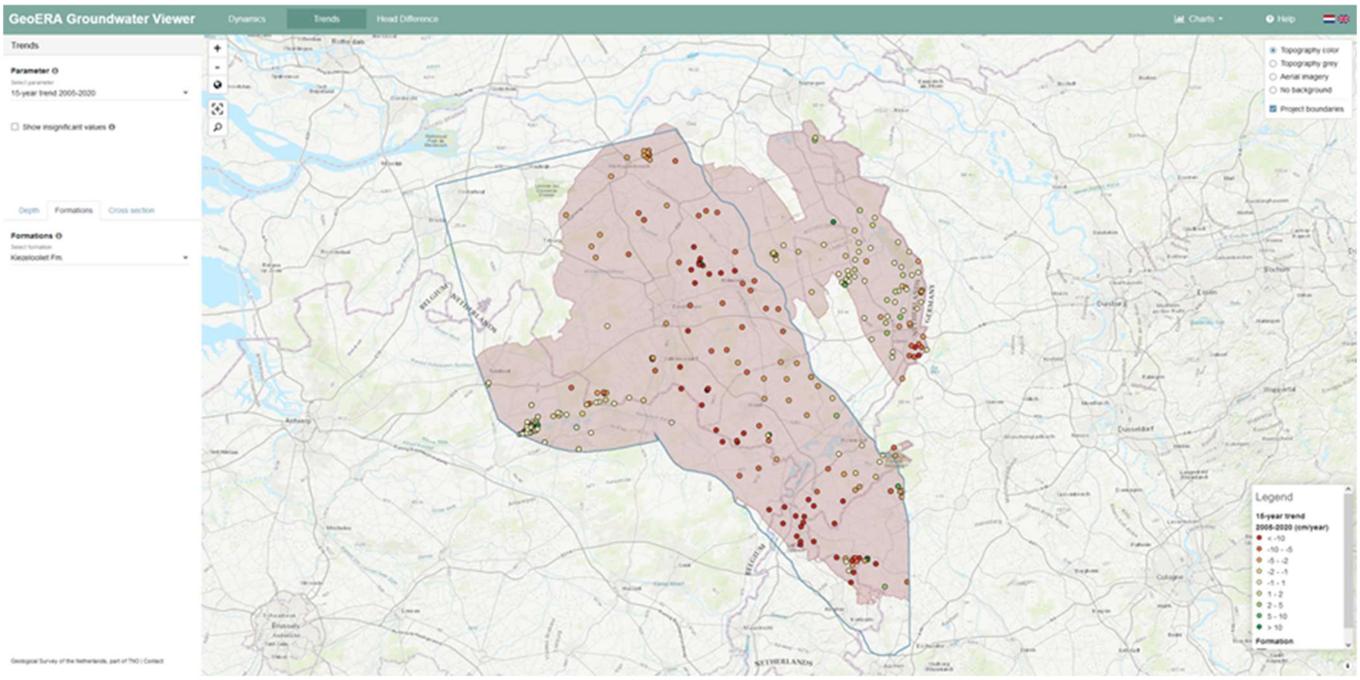

Figure 3.4 Assessing trend per geological Formation: example: the Kieseloolite Formation

Figure 3.4 shows that a large number of decreasing trends are found in the Kieseloolite Formation for the period 2005-2020, especially for screens that are located in the Roer Valley Graben where the Kieseloolite Formation is found at larger depth. Trends are much less outspoken for the Flemish part of the Kieseloolite Formation and for the Kieseloolite Formation in the Peel Block and the adjacent Venlo Graben to the east. We may now choose to either look at specific monitoring points within the Kieseloolite Formation, by clicking one of the observation wells, or choose a shape-free area for which we are interested in the overall trend, or as we call it: the spatially *Aggregated Trend*. We chose “Select area” and selected a polygon around the main part of the Roer Valley Graben (Figure 3.5) for assessing those aggregated trends.

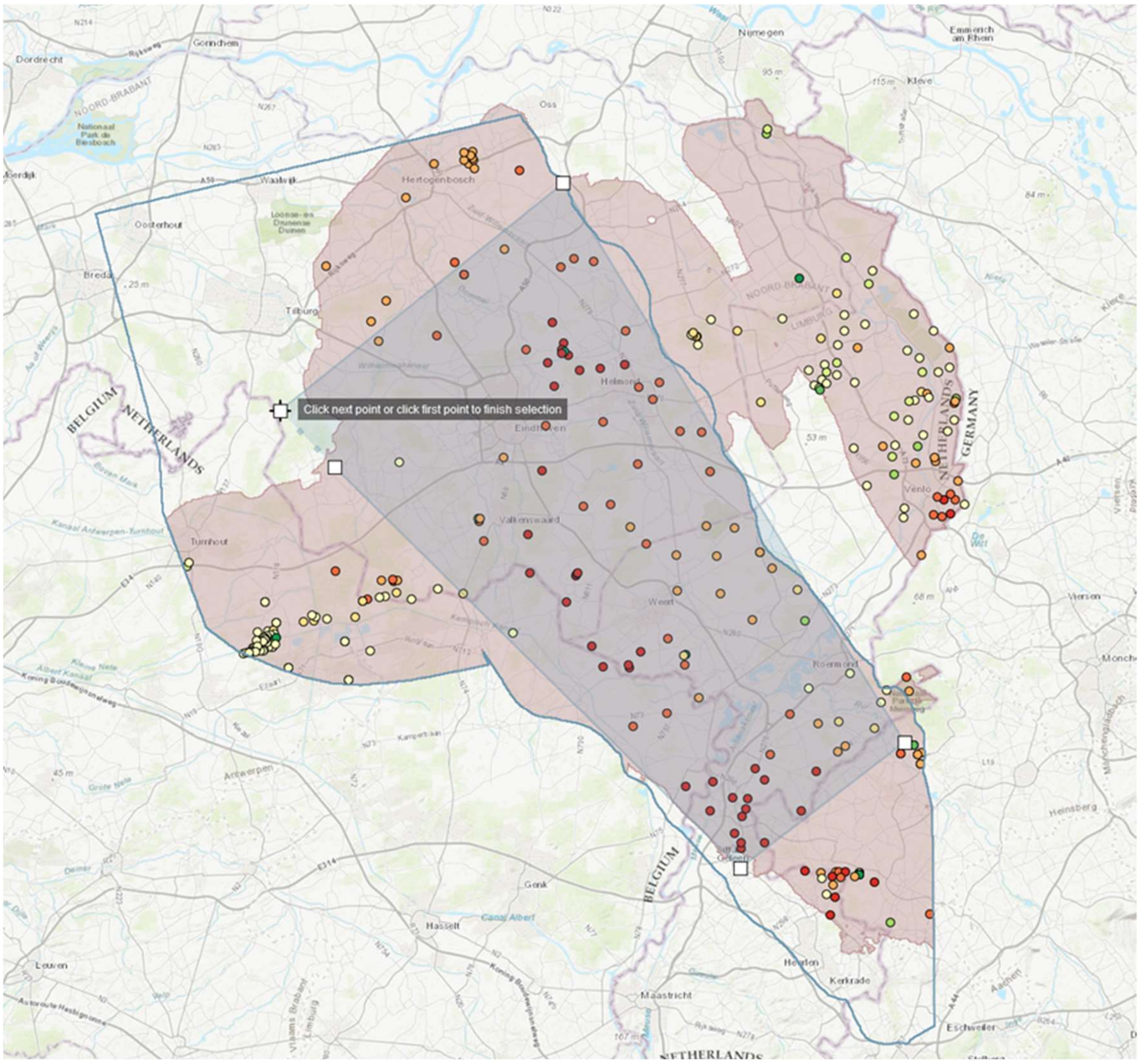

Figure 3.5 Choosing an area to assess “aggregated trends” over multiple periods

Figure 3.6 shows the results of the Aggregated Trends for the Kieseloolite Formation in the selected part of the Roer Valley Graben. The aggregated trend indicates an overall decreasing trend between 1980 and 2000, a slightly increasing trend over 1995-2010 and a further decrease between 2005 and 2020. This pattern is indeed found in many time series of individual screens and seems to be an overriding pattern for the whole of the Kieseloolite Formation in the Roer Valley Graben.

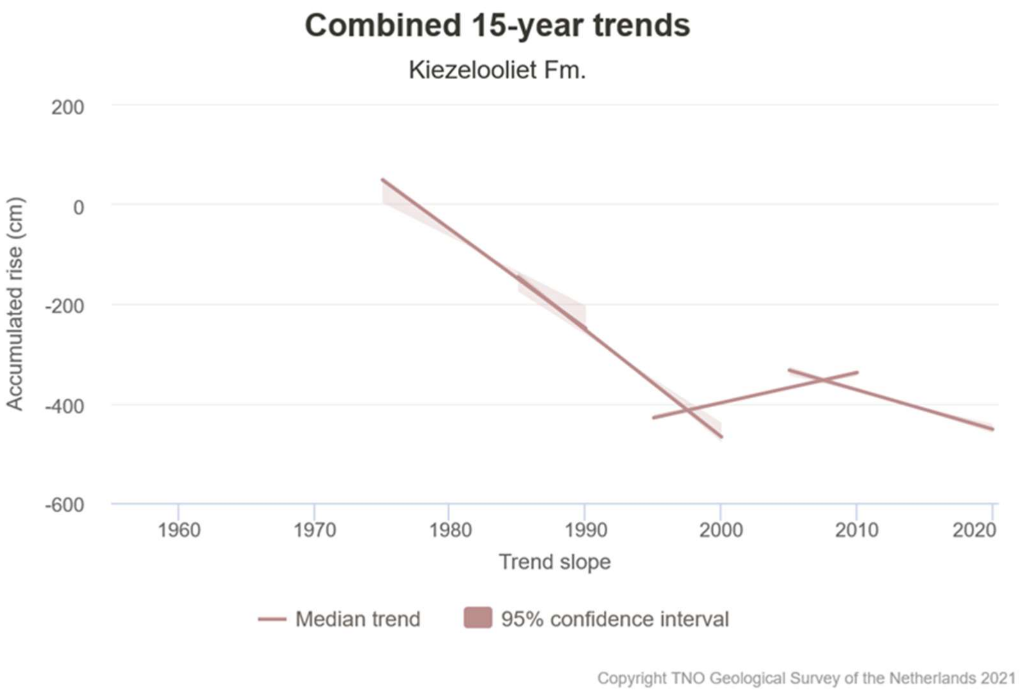

Figure 3.6 Aggregated trends over multiple 15-years long monitoring periods for the observation wells in the Kieseloolite Formation.

Instead of selecting one geological formation, we may also select multiple formations. Selecting the Sterksel Formation, the combined Peize-Waalre Formation and the Kieseloolite Formation enables direct comparison of the relative number of time series with trends over the period 2005-2020 (Figure 3.7).

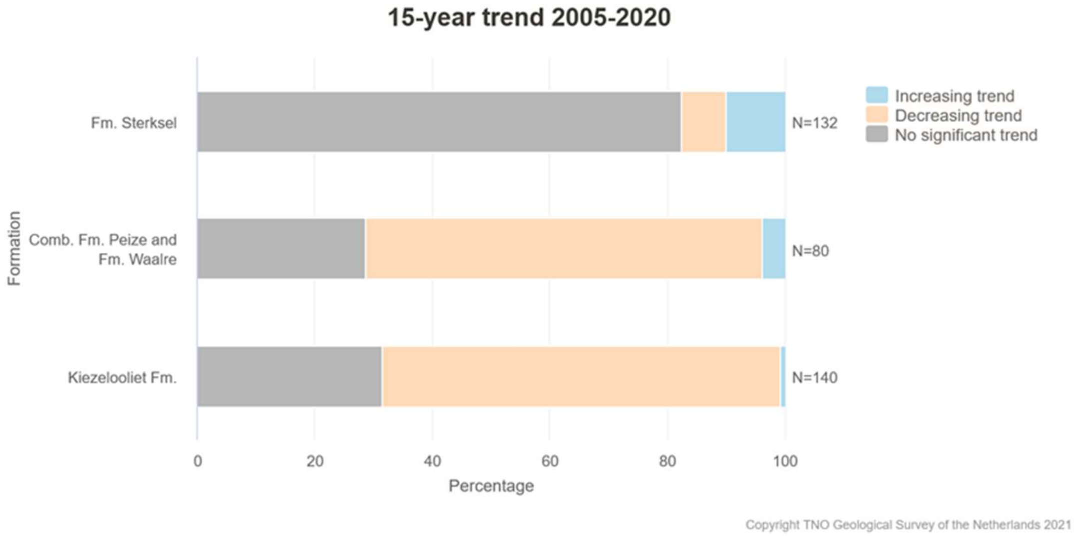

Figure 3.7 Assessing trends for 3 geological Formations for the area selected in Figure 3.5. The Sterksel Formation shows fewer decreasing trends than the deeper Formations of Peize/Waalre and Kieseloolite.

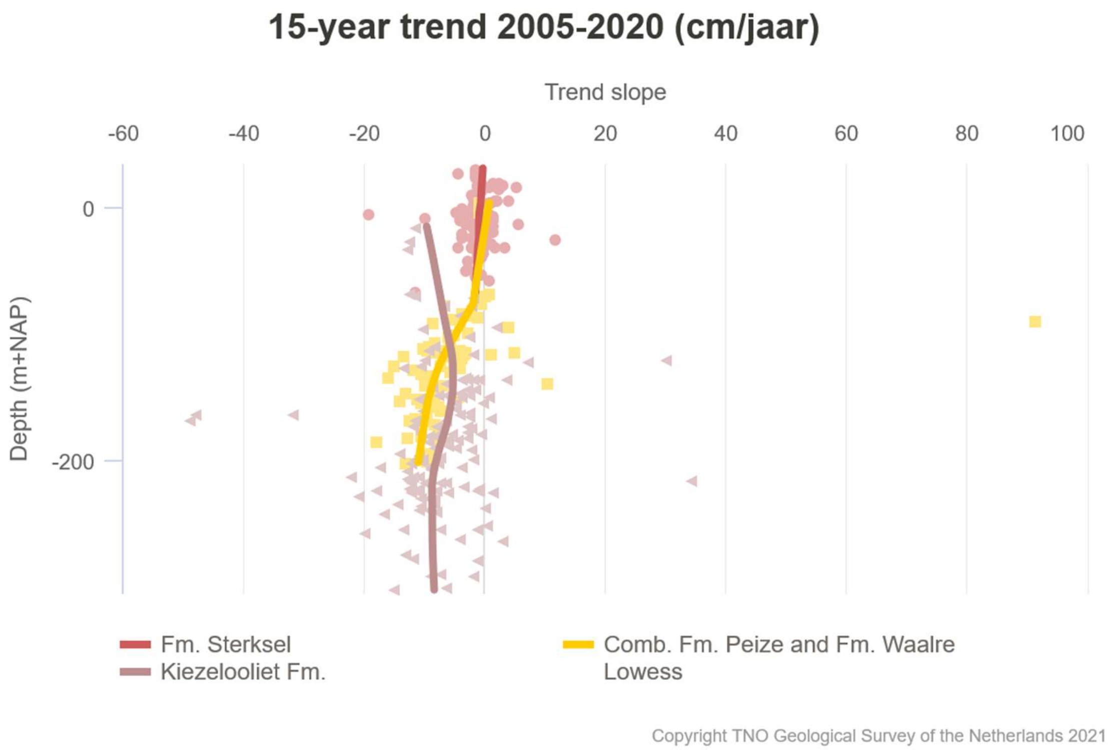

Figure 3.8 Relation between depth and the magnitude of the temporal trend for 3 geological formation in the Roer Valley Graben. The upper Sterksel Formation gives no indication for an overall decreasing groundwater heads over the period 2005-2020, whereas a clear signal of decreasing groundwater heads of 10 cm per year is found for screens in the deeper part of the Peize/Waalre Formation and the Kieseloolite Formation. Lowess = locally weighted scatterplot smoothing.

Figure 3.7 and Figure 3.8 can be automatically generated after choosing the geological Formations and selecting an area to aggregate the trend information. Figure 3.8 gives an important hydrological signal: there are no indications for a clear overall decreasing groundwater head over the period 2005-2020 in the fluvial Sterksel Formation and the shallowest parts of the Peize/Waalre Formation. However, there is a clear signal of decreasing groundwater heads of 10 cm per year for filters in the deeper part of the Peize/Waalre Formation and the Kieseloolite Formation. This pattern of decreasing groundwater heads is also apparent for the underlying Oosterhout Formation (Figure 3.9) and the even deeper Breda Formation (not shown).

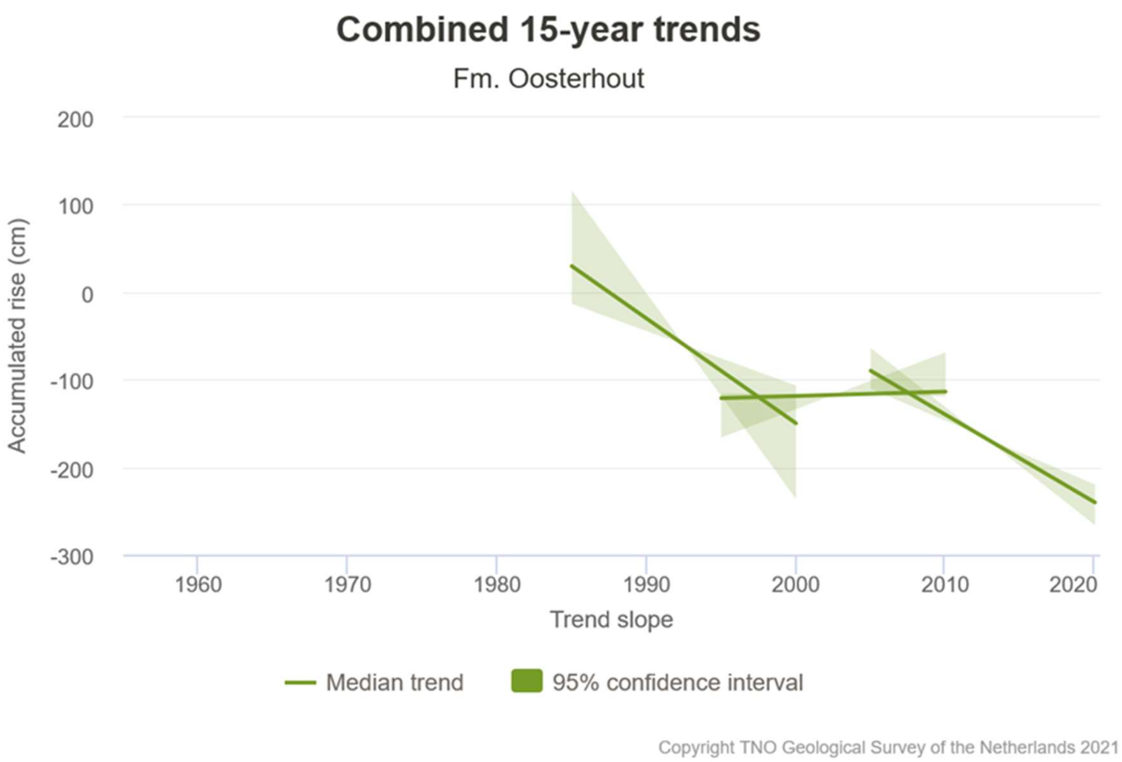

Figure 3.9 Aggregated trends for the Oosterhout Formation in the Roer Valley Graben.

3.1.3 Understanding the long-term trend pattern in the Roer Valley Graben

The overall pattern that was found for the groundwater heads in the Roer Valley Graben indicates a period with increasing or stable groundwater heads over the period 1995-2010 (Figure 3.6 and Figure 3.9) with declining trends before and after that period. This pattern is visible in many individual observation wells, for which well B51E0078 filter 6 serves as an example (Figure 3.10) but we could have chosen many other wells for the same analysis. In correspondence with the aggregated trends of Figure 3.6 and Figure 3.9, the individual time series of Figure 3.10 shows a similar wave with groundwater heads decreasing between 1985 and 1995, an upward sequence between 1995 and 2010 and a further downward trend since then.

This pattern was not really expected beforehand and after some further analysis we hypothesize that the "wave" in the time series is related to a long-term wave in the net groundwater recharge which is due to meteorological/climatological inputs. It seems that the groundwater recharge signal is transformed towards the groundwater heads under the main Waalre aquifer (PZWAk1) following a 20-year moving average of the net recharge. This hypothesis is further corroborated in Chapter 4.

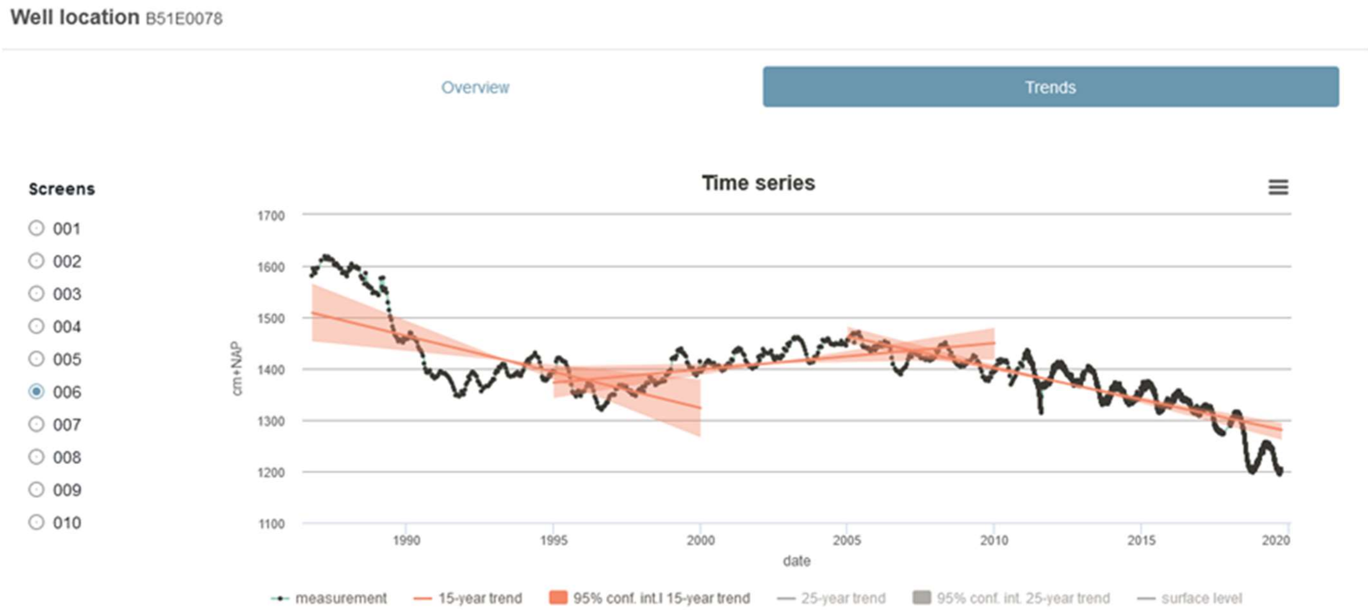

Figure 3.10 The "wave" in the groundwater heads illustrated for observation well B51E0078 filter 6 in the Oosterhout Formation at -251 m depth in the Roer valley Graben.

3.1.4 Assessing trends through cross-sections

Finally, information on groundwater head trends can be visualized using cross-sectional views of which Figure 3.11 is an example. The patterns that were identified in the previous sections also appear in the cross-sectional view. The downward trends are concentrated in aquifers that are exploited for drinking water supply, but we also found indications for the effects of groundwater pumping for irrigation (see Chapter 4).

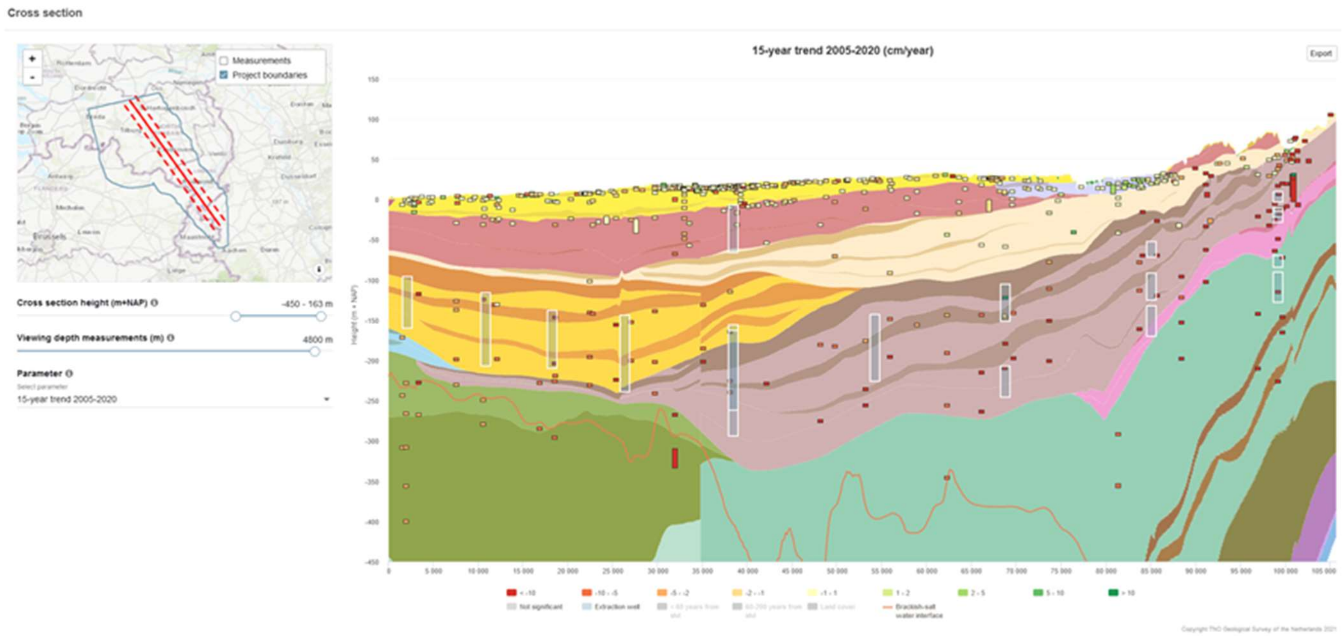

Figure 3.11 Temporal trends over the period 2005-2020 for a longitudinal cross-section through the Roer valley Graben. Red symbols denote a decreasing groundwater trend of more than 10 cm year^{-1}. Downward trends are abundant in the Peize/Waalre (yellow and orange), Kieseloolite (brown/purple) and Oosterhout and Breda Formations (olive-green and blue-green). White rectangles indicate the position of public supply well fields that fall within the red dashed zone in the upper left figure.

3.2 The updated groundwater Head Differences tool

Entering through the Head Difference menu, similarly as for the Trend tool, the user has three main directions to discern information about head differences between monitoring screens:

1. Selecting a depth range under the depth submenu
2. Selecting one or more geological formations
3. Selecting a transect for visualizing a hydrogeological cross-section with head differences information superposed.

By means of the updated Head Differences tool, we may now acquire information on aggregated head differences for a selected area and the selected depth range, or for the selected area and the selected geological formations.

3.2.1 Assessing head differences over a certain depth range

Figure 3.12 gives the result for vertical groundwater head differences of a selection of the depth range - 20 m below mean sea level (NAP) plus or minus 20 m for the period 2005-2020. The tool is similar to the trend tool having the option to look at vertical groundwater head differences over different periods, which coincide with the periods in the Trend tool. Changes in head differences over time can be very clarifying about changes in the groundwater circulation, for example because of changes in pumping regimes or changes in climatological conditions. In the maps of head differences, blue colours denote potential upward flow (deep head higher than shallower head) and red colours indicate downward flow (deeper head lower than shallower head). A closer look at the result of Figure 3.12 reveals that blue colours and upward flow are concentrated in the main brook valleys, known regional groundwater discharge areas and the polders in the northwest of Noord-Brabant. Red colours dominate in areas with substantial groundwater recharge to deeper aquifers or in areas with aquitards with high vertical hydraulic resistance.

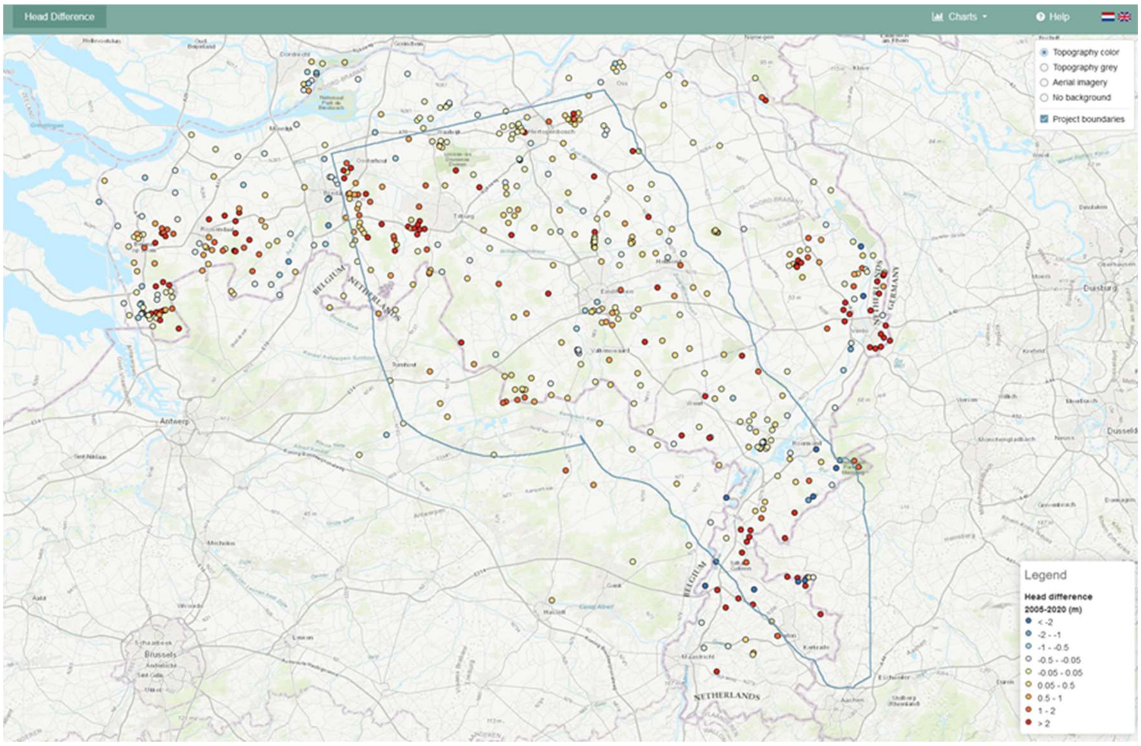

Figure 3.12 Vertical Head Differences for screens which are situated between 20 m -NAP ± 20 which corresponds to depths between 0 m and 40 m -NAP.

Selecting one of the points on the map brings the user to the "Coherence between Screens" tab of the Time Series Menu (see Figure 3.13). Selecting one of the points with a large head difference in the region of Tilburg reveals that a 3 m head difference is present between the Stramproy Formation (SY) and the underlying Peize/Waalre and Maassluis Formations (Figure 3.13). The phreatic groundwater head in the Stramproy Formation fluctuates around +13 m NAP, whereas the groundwater head in the Peize/ Waalre and Maassluis Formations fluctuates around + 10 m NAP. By selecting the *"All"* tab just above the time series graphs, the complete time series of an observation well can be visualized and the temporal change in the head difference, if any, becomes apparent. The option to assess head differences over the complete recording history is one of the new features of the web viewer. In the initial viewer version, this was only possible for an 8-year period.

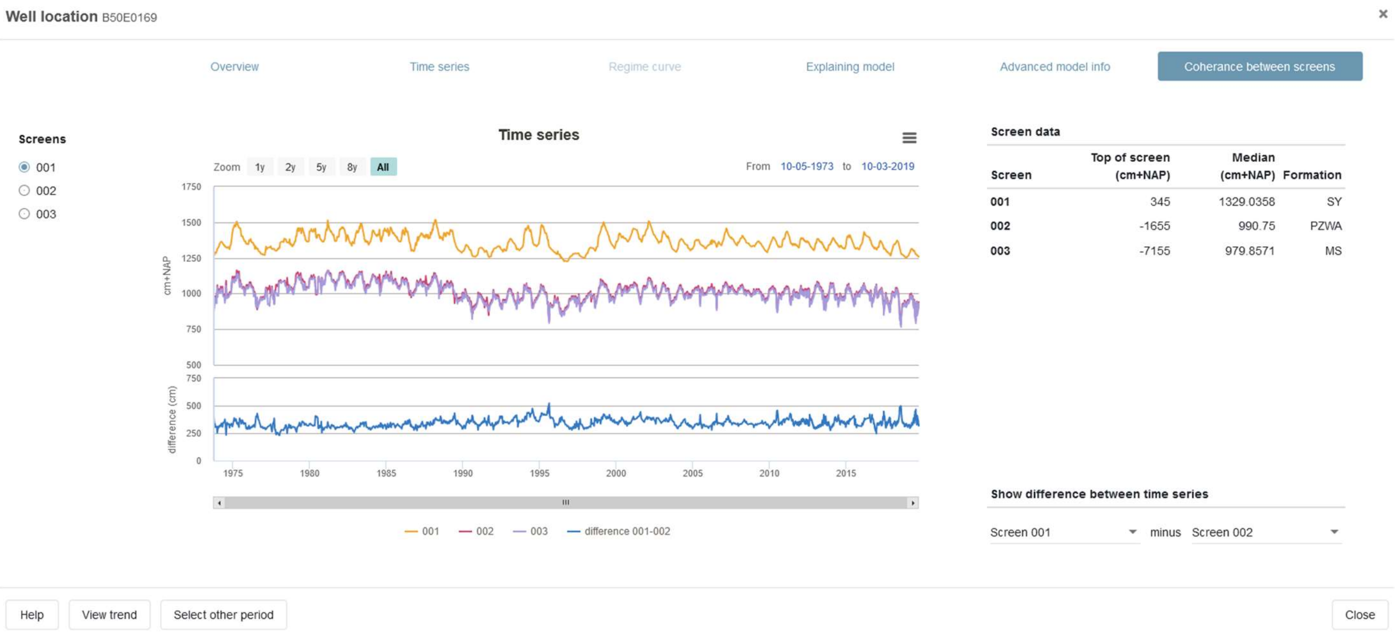

Figure 3.13 Vertical Head Difference (blue line) between screen 01 (Stramproy Formation) and screen 2 (Peize/Waalre Formation) for observation well B50E0169 near Tilburg.

In the case of well location B50E0169, the study of the complete time series reveals that the head difference peaks up to 5.0 m during the dry summers of 2018 and 2019 and the dry winter of 1996. These peaks correspond with sharply dropping water levels in the observation screens of the Peize/Waalre and Maassluis Formations, which are most probably due to increased pumping from these aquifers during the dry seasons. The head difference does not enclose a clear long-term trend over the entire period, although the was an increasing trend from ~1982 until 1996.

3.2.2 Assessing head differences for geological formations

The updated version of the GeoERA webtool now enables selections of geological formations to study head differences. By selecting one of the geological formations all screens in the formations are compared with screens either above or below the selected formation. Again, blue colours indicate upward flow and red colours downward flow.

3.2.2.1 The Kieseloolite Formation

Figure 3.14 illustrates the potential of such an analysis using the Kieseloolite Formation as an example. The Figure shows a number situations for the Kieseloolite Formation:

- Downward flow to deeper parts of the Kieseloolite Formation and underlying Oosterhout Formation in zone (I) indicating that there is recharge from shallower layers through the main aquitard at the top of the Kieseloolite Formation into deeper layers
- Upward flow from the Kieseloolite Formation to the Meuse valley in region II
- Upward flow towards the Peize-Waalre Formation in region III which is related to a northerly direction of groundwater flow and the Kieseloolite Formation wedging out towards the north. As a result, groundwater is forced upward into the

Peize/Waalre Formation, a process which is intensified by substantial groundwater pumping in the shallower Peize/Waalre Formation (see also Figure 3.21)
- Downward flow in region IV, which forms a regional recharge area where the Kieseloolite Formation and the overlying Stramproy Formations are relatively close to the surface.

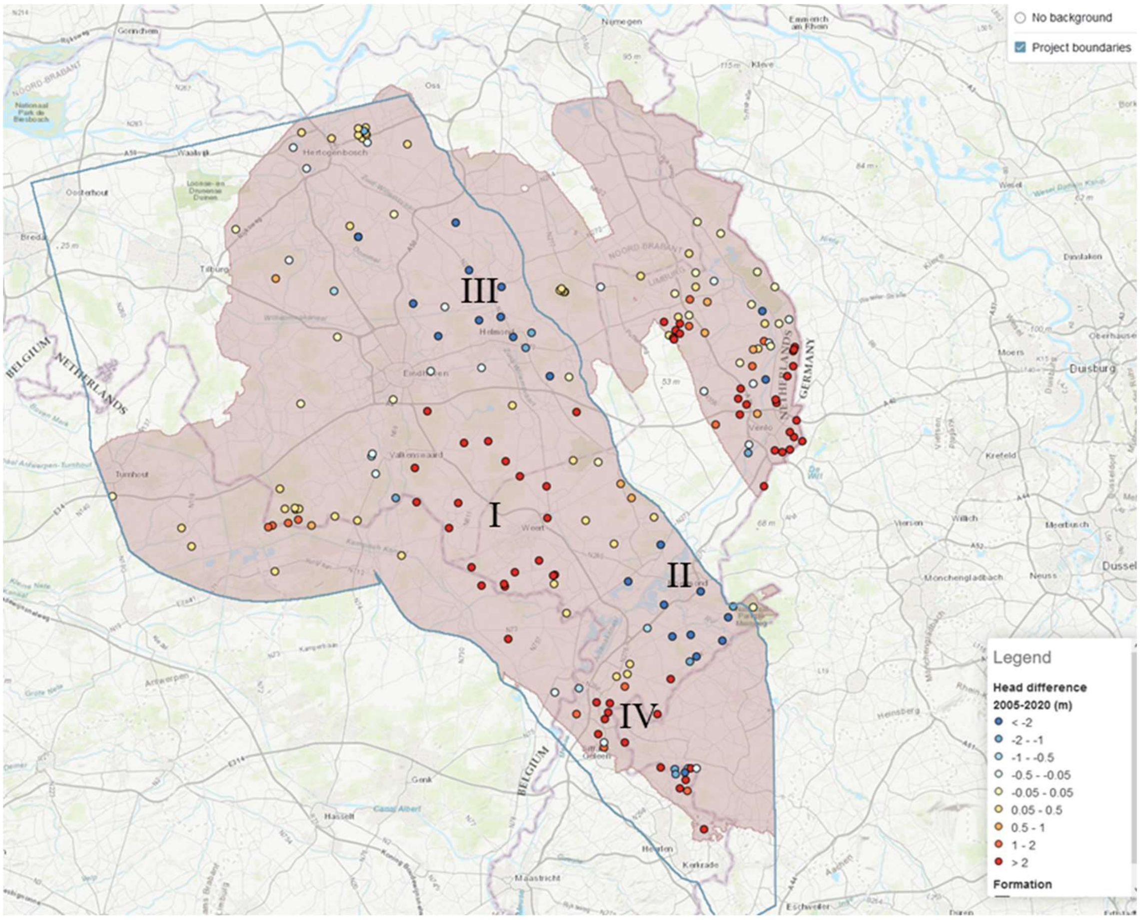

Figure 3.14 Head differences relative to the filters in the Kieseloolite Formation. The colours in the map depict the head difference between screens in shallower formations than the Kieseloolite Formation and screens in this Formation. Blue colours indicate upward flow from the Kieseloolite Formation to shallower layers. Red colours denote downward flow from shallower Formations towards the Kieseloolite Formation.

The regions indicated in Figure 3.14 can now be compared with the fluxes modelled in the IBRAHYM-ROERDAL model which have been assessed by Buma & Reindersma (2021). Figure 3.15 shows these fluxes and the comparison between measurements in Figure 3.14 and model results in Figure 3.15 shows reasonable agreement for the regions I, II and IV. For region III the situation is complicated because the Kieseloolite Formation wedges out to the North. Moreover, the model schematization makes a direct comparison impossible (for details, see Buma & Reindersma, 2021).

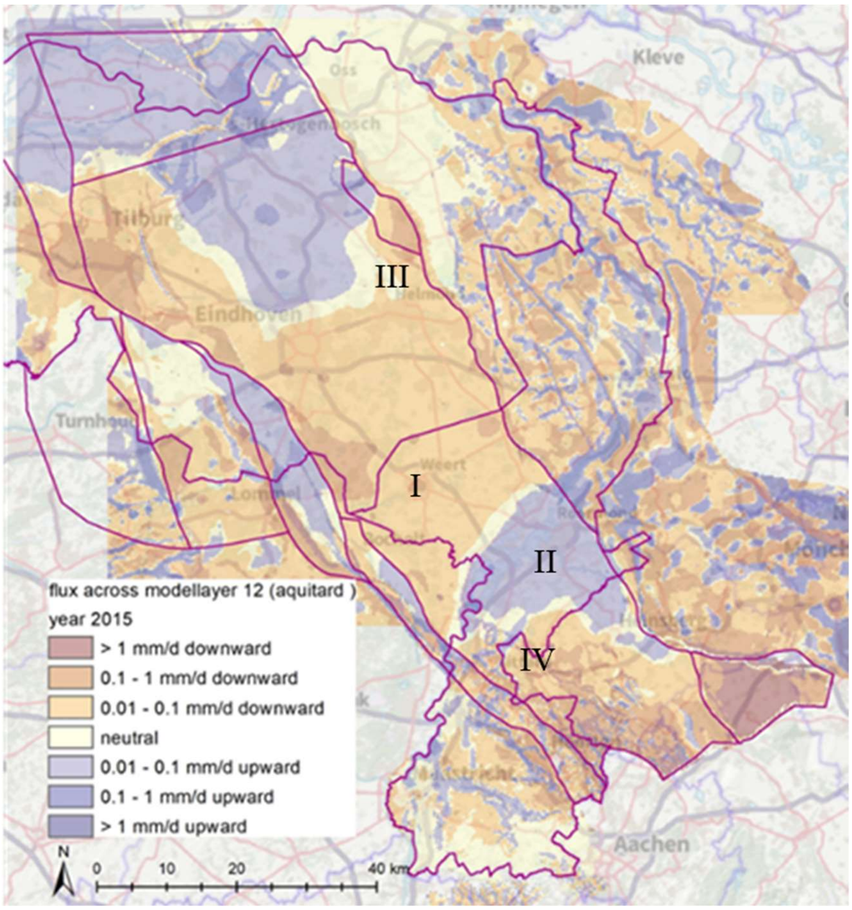

Figure 3.15 Vertical Fluxes over the aquitard at the top of the Kieseloolite Formation based on the IBRAHYM-ROERDAL model (version 2) as analysed in GeoERA RESOURCE Deliverable 3.4 (Buma et al. 2021)

The update of the web viewer now allows to aggregate the data on head differences between the aquifers in a direct way. Figure 3.16 illustrates the head differences between all the screens in the Kieseloolite Formation and in all other formations in the Roer Valley Graben. The Figure indicates that flow from the shallower Beegden, Sterksel and Stramproy Formations is downward towards the Kieseloolite Formation in the majority of cases, and head differences are in the order of 3 meters. In areas where the Kieseloolite Formation is present below the Peize/Waalre Formation, flow tends to be upwards towards the Peize/Waalre and the median head difference ranges between 0 and -4 meter. Head differences with deeper Maassluis, Oosterhout, Breda and Inden Formations are all limited to < 1 m and the groundwater head in the Kieseloolite Formation tends to be a bit higher than in those Formations, indicating downward fluxes.

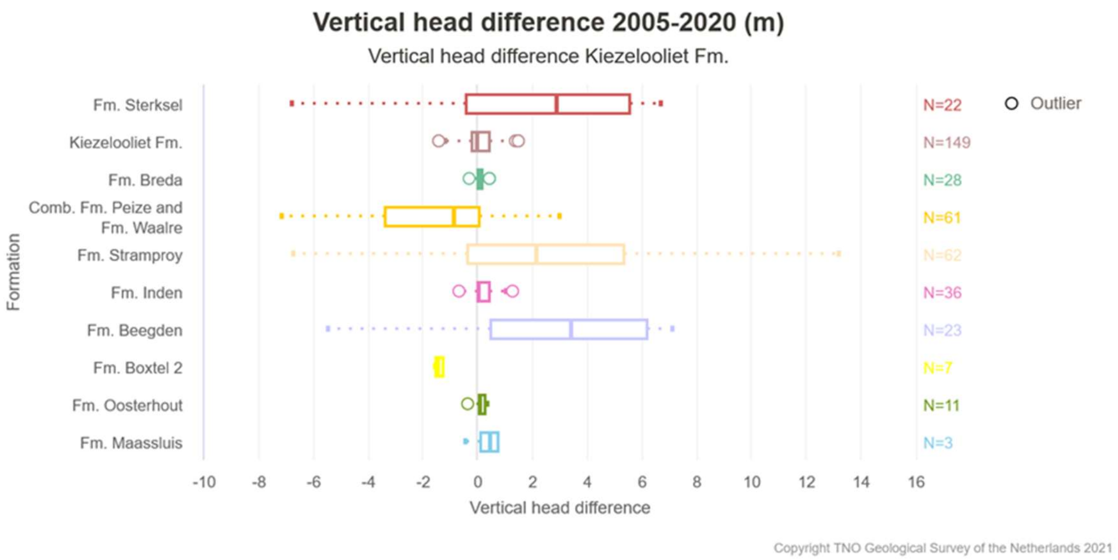

Figure 3.16 Head differences between the Kieseloolite Formation and all other Formations which are present in the Roer Valley Graben. Positive numbers indicate downward flow, negative numbers indicate upward flow directions.

3.2.2.2 The Peize/Waalre Formation

Assessing the head differences between the formations in the Roer Valley Graben, it appeared that especially the Peize/Waalre Formation takes a prominent position as groundwater heads tend to be lowest in this specific formation. Figure 3.17 shows the map of the head differences between the Peize/Waalre Formation and the shallower aquifers.

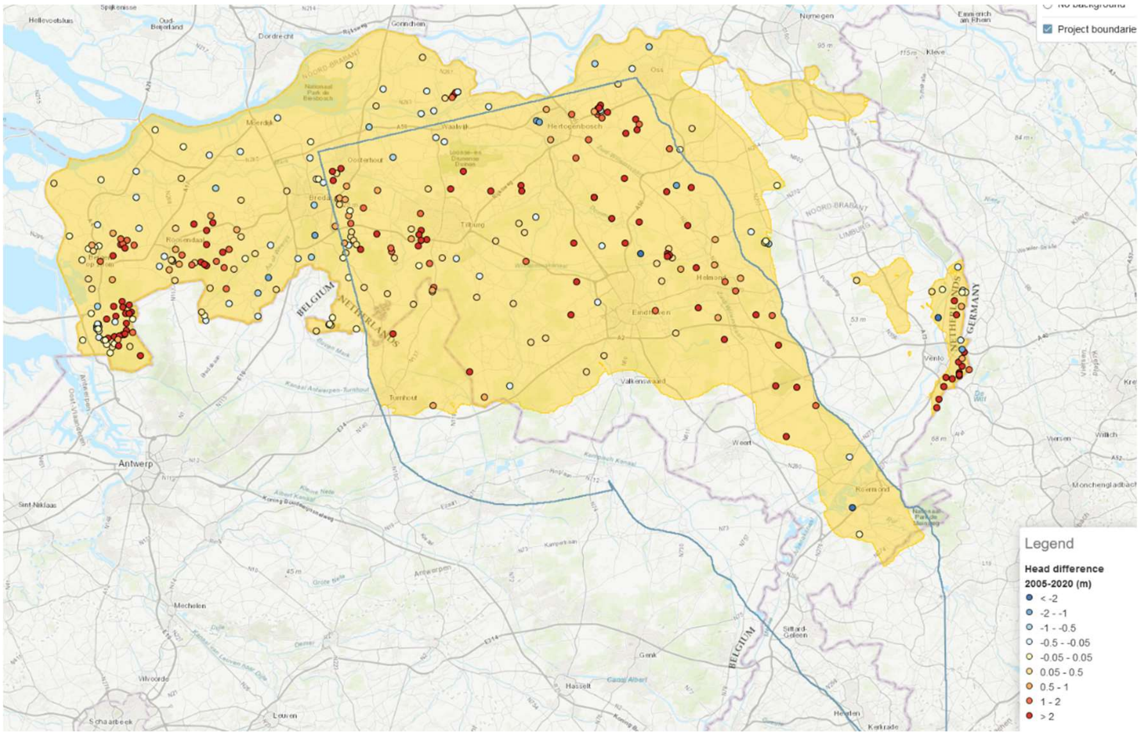

Figure 3.17 Head differences relative to the filters in the Peize/Waalre Formation. The colours in the map depict the head difference between screens in shallower formations than the Peize/Waalre Formation and screens in this formation. Blue colours indicate upward flow from the Peize/Waalre to shallower layers. Red colours denote downward flow from shallower Formations towards the Peize/Waalre Formation.

Figure 3.18 shows that the head difference between the overlying Sterksel and Stramproy Formations is mostly positive with a 25- and 75-percentile of 1 and 3.5 m, respectively, for the Sterksel and a 25- and 75-percentile of 0.5 and 3 m for the Stramproy.

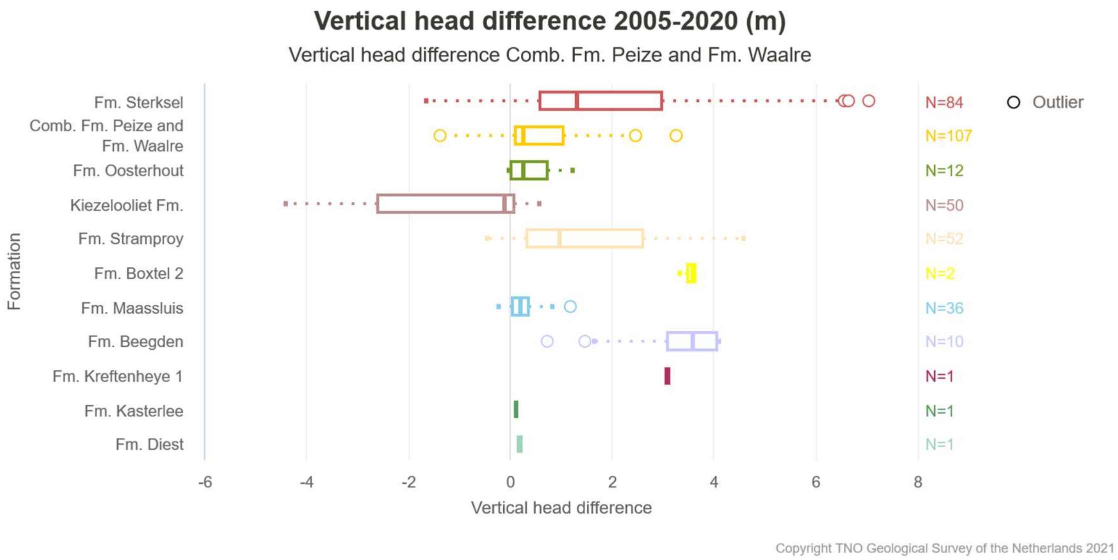

Figure 3.18 Head differences between the Peize/Waalre Formation and all other Formations which are present in the Roer Valley Graben. Positive numbers indicate downward flow, negative numbers indicate upward flow directions.

The updated tool further enables to study other periods for head differences. For example, choosing the period 1965-1980 to study head differences, a number of observation wells is available to study historical head differences in the Roer Valley Graben. The tool reveals that quite a number of the head differences between the Peize/Waalre and overlying Formation have increased more than 5 m since 1970.

An example of time series long enough for such an analysis is given in Figure 3.19. Well B51B0073 near Son and Breugel shows a head difference between the overlying Sterksel and Boxtel Formations and the Peize/Waalre Formation which increased by more than 10 m since the start of the measurements in 1970. The head difference starts in 1973 at the starting of a new well field for drinking water supply at Son and not representative increased steadily over the last 35 years. This is a local change in close proximity of the Son public supply well field and not representative of the overall change in the head differences over the Roer Valley Graben.

The most important message of Figure 3.19, however, is the observation that the head differences between the Sterksel Formation and the Peize/Waalre Formation were negligible in 1972. Which means that the head difference between these formations is artificial and completely determined by abstractions from the Peize/Waalre aquifers below the main PZWAk1 aquitard. Long time series like the one from B51B0073 are relatively scarce, but the ones that are available give the same information: negligible or small head differences or even differences indicating potential artesian conditions before the start of the centralized water supply from the aquifers below the main aquitard in the Roer Valley Graben.

As such, it proves the capabilities of the web viewer to identify such major influences on the groundwater circulation in the Graben, as the identification of long time series and long time series that indicate head differences have now been made more accessible by dedicated selection procedures in the tool.

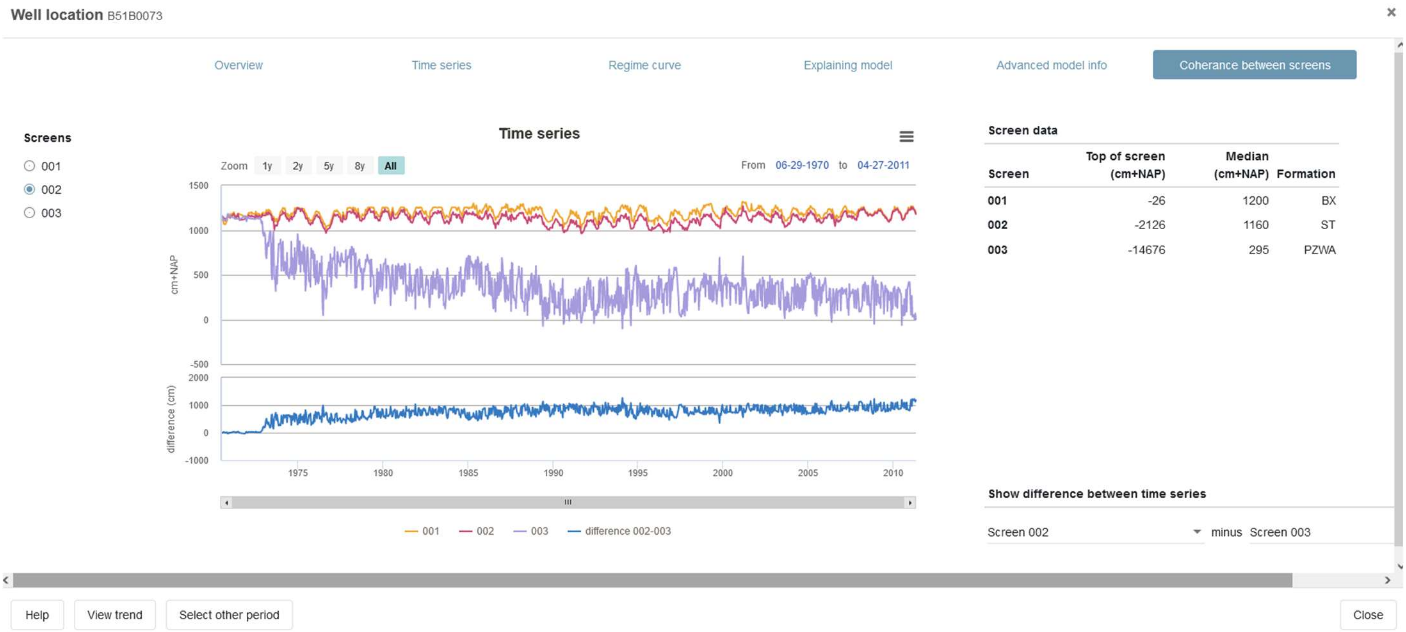

Figure 3.19 Head differences in well B51B0073 shows a head difference between the overlying Sterksel and Boxtel Formations and the Peize/Waalre Formation which increased from near zero in 1970 to + 10 m in 2011.

The overall head differences between the Peize/Waalre Formation and the overlying Sterksel and Stramproy Formations correspond to the findings of Buma et al. (2021) who evaluated the results of the IBRAHYM-Roerdal model for fluxes over the main PZWAk1 aquitard which is located at the top of the Peize/Waalre Formation (Figure 3.20). The orange overlay in Figure 3.20 indicates the zone in the Roer Valley Graben where the flux over the PZWAk1 towards the lower Peize/Waalre aquifers is predominantly downward, which is confirmed by the measured head data as revealed by the GeoERA web viewer(Figure 3.17, Figure 3.18, Figure 3.19).

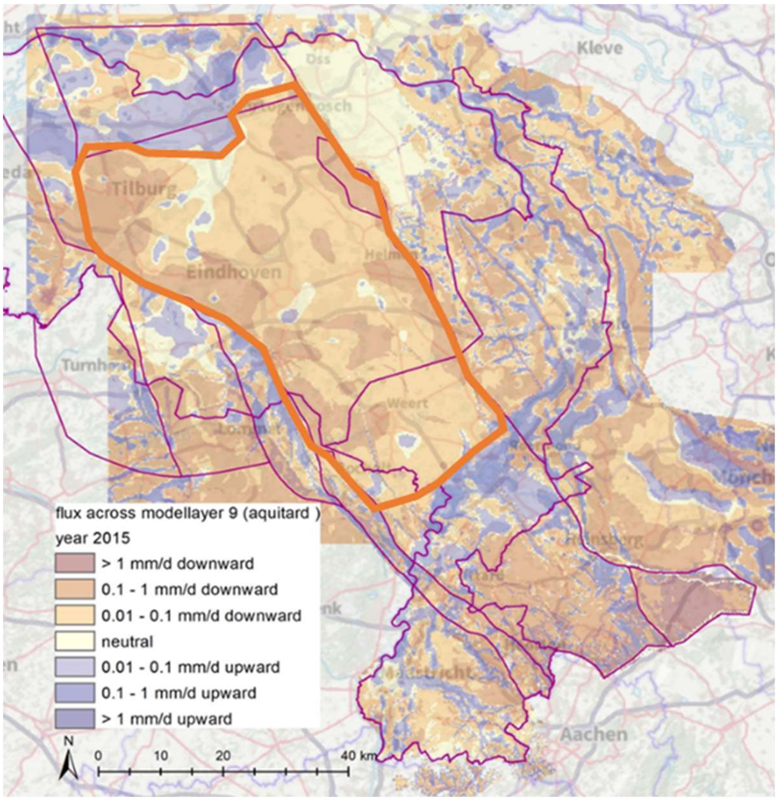

Figure 3.20 Vertical Fluxes over the PZWAk1 Aquitard based on the IBRAHYMROERDAL (version 2) as analysed in GeoERA RESOURCE Deliverable 3.4 (Buma et al. 2021). Overlay in orange indicates the zone in the Roer Valley Graben where the flux over the PZWAk1 towards the lower Peize/Waalre aquifers is predominantly downward.

3.2.3 Assessing head differences in cross-sections

Further information about head differences can be visualized using the cross-section tool in the GeoERA webtool. Figure 3.21 demonstrates the use of the tool for a longitudinal section through the Roer Valley Graben, with an indication of the areas which were identified in Figure 3.14. In the cross-section, it is easier to demonstrate how the Kieseloolite wedges out in northerly direction (to the left in the Figure) and how the PZWAk1 aquitard takes over the role of most important aquitard from South to North in the profile. The wedging out of the Kieseloolite forces the northerly lateral flow in this formation upward. This effect is strengthened by a number of water supply abstraction sites which pump water from the overlying Peize/Waalre Formation in the downstream part of the cross-section. So, the groundwater in the Kieseloolite Formation is forced upwards both by the declining thickness of the Kieseloolite aquifers and by the groundwater head decline in the Peize/Waalre aquifers due to pumping.

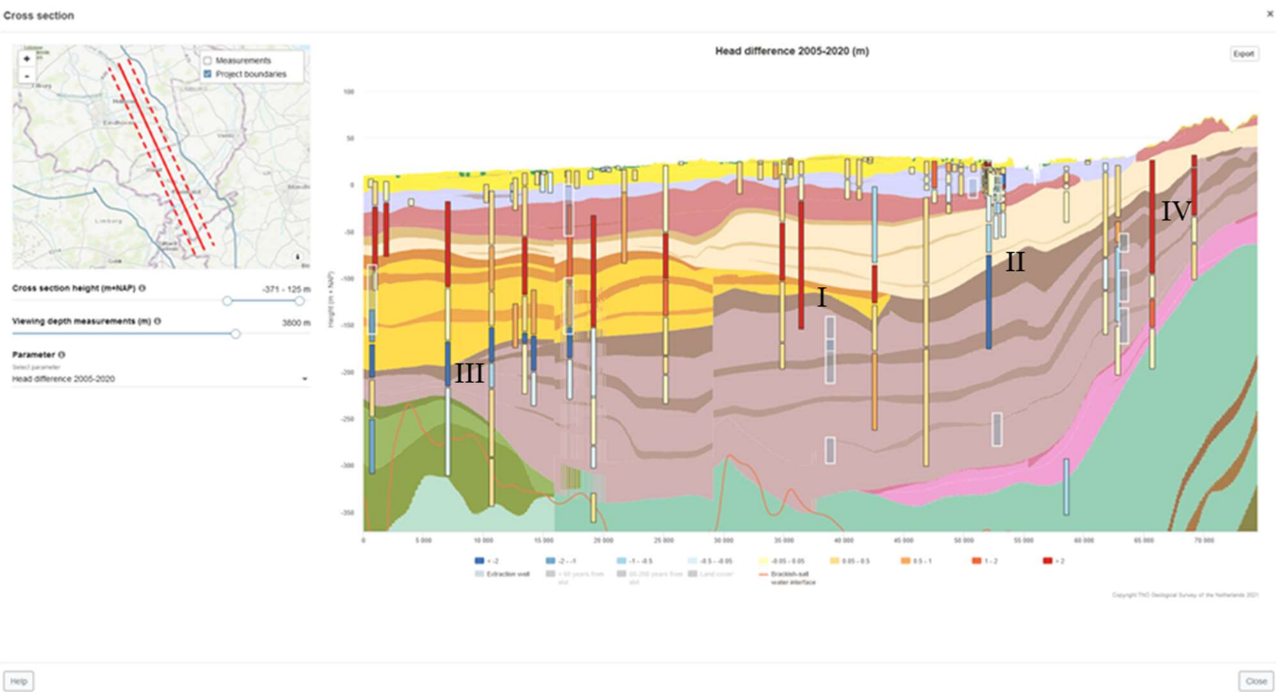

Figure 3.21 Cross-section from NW to SE showing the regions which are mapped in Figure 3.14. Head differences are shown as blue or red bars between the top of a screen at the lower end of the bar and the bottom of the next shallower screen in an overlying formation. Red bars indicate downward flow, blue bars indicate upward flow.) Typically, a large head difference between two screens coincides with a low permeable layer between the two screens which are typically placed in aquifers. Low permeability layers have a darker tone and aquifers have a lighter tone of the same colour per Formation. White rectangles indicate the position of public supply well fields that fall within the red dashed zone in the upper left figure.

4 FURTHER ANALYSIS OF THE GENERAL HEAD EVOLUTION IN THE DEEPER FORMATIONS OF THE ROER VALLEY GRABEN

The overall pattern that was found for the groundwater heads in the Roer Valley Graben indicates a period with increasing or stable groundwater heads over the period 1995-2010 with declining trends before and after that period. This pattern is visible in many individual observation wells, for which well B51E0078 filter 6 serves as an example (Figure 3.10, reproduced here as Figure 4.1). The aggregated trends of Figure 3.6 and Figure 3.9 reveal that this pattern is quite general for the deeper formations in the Roer Valley Graben.

This pattern was surprising because there was no change in groundwater use for public water supply that could have caused this increase between 1995 and 2010 and the influence of precipitation and evaporation seems to be represented in the annual fluctuations which are reflected in the time series. We hypothesize that the “wave” in the time series is related to a long-term wave in the net groundwater recharge which is due to meteorological/climatological inputs. It seems that the groundwater recharge signal is transformed towards the groundwater heads under the main Waalre aquifer (PZWAk1) following a 20-year moving average of the net recharge. In this Chapter we try to corroborate this hypothesis.

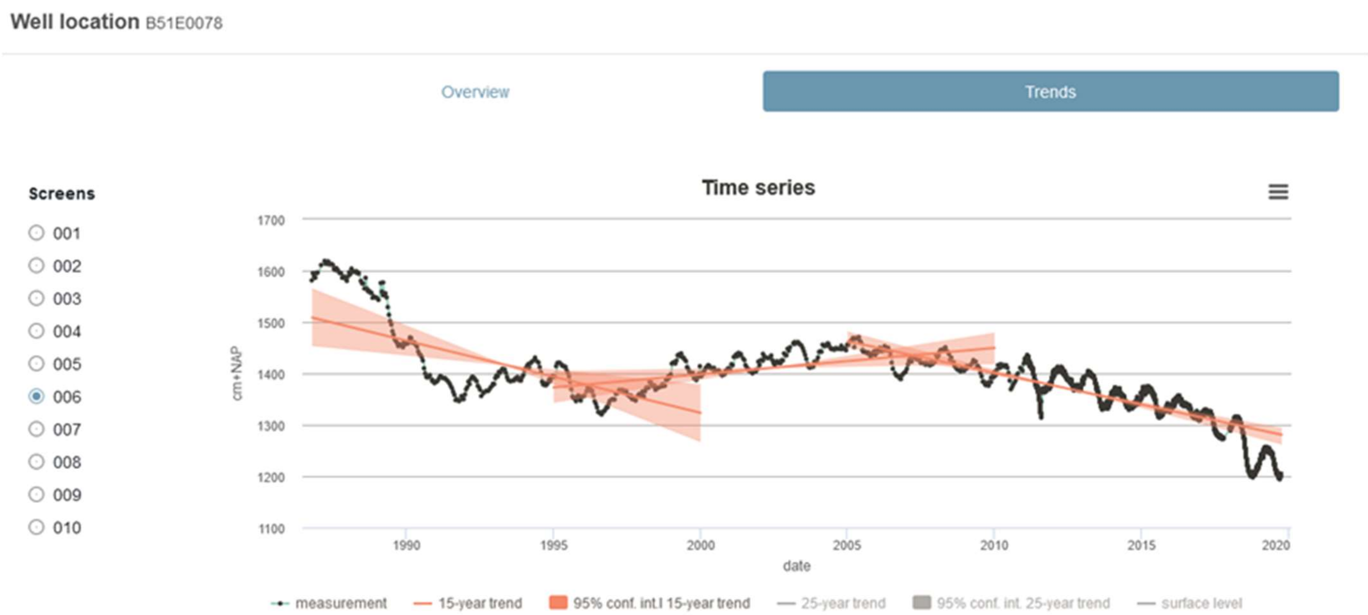

Figure 4.1 The “wave” in the groundwater heads illustrated for observation well B51E0078 filter 6 in the Oosterhout Formation at -251 m depth in the Roer valley Graben

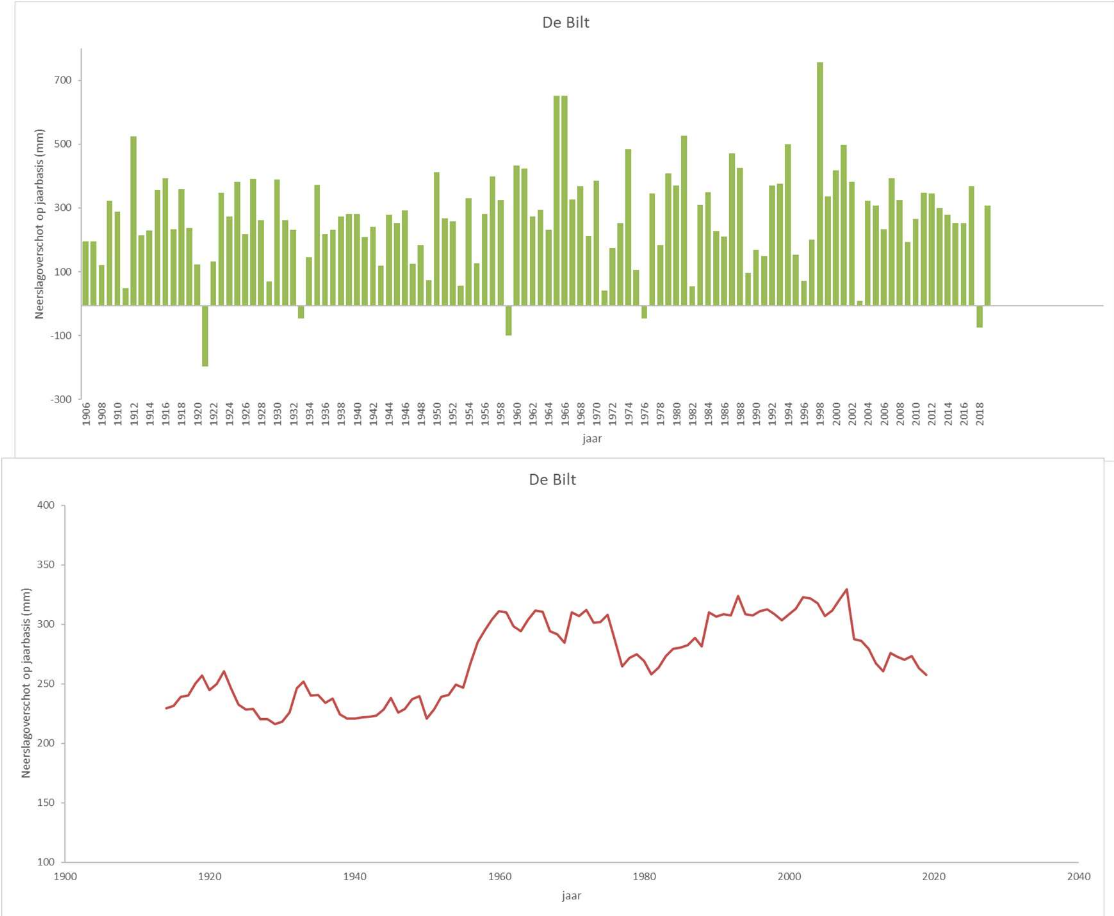

Figure 4.2 Annual precipitation surplus (precipitation minus Makkink evaporation (mm year^{-1}) at De Bilt meteorological station (top) and 20-year moving average (bottom).

As a first step, we evaluated yearly total of the precipitation surplus, which is defined as the difference between precipitation and Makkink evaporation. For the main meteorological station of the Royal Dutch Meteorological Institute (KNMI) at De Bilt, values are available for more than a century (Figure 4.2).

We use this precipitation surplus as a proxy for the net groundwater recharge for areas which are not drained by ditches or drains, have permeable soils, and groundwater tables that are not too deep beyond the vegetation root zone.

The yearly total in the top part of Figure 4.2 show a negative net recharge for the dry years of 1921, 1933, 1959, 1976 and 2018 and a large positive value for wet years of 1965, 1966 and 1998. Overall, the period 1987-2012 had a relatively large precipitation surplus and potentially a large net groundwater recharge.

The bottom part of Figure 4.2 shows a long-term variation in the 20-year moving average over the net precipitation surplus which shows resemblance to the slow general pattern found for the deeper groundwater heads in the Roer Valley Graben, albeit with a time shift. This suggests that the groundwater heads may be influenced by a slow response to precipitation and evaporation in addition to the faster response that is connected to the seasonal variation of the groundwater heads which is visible as fluctuations in Figure 4.1.

We tested this hypothesis with transfer function-noise modelling of groundwater heads using the Metran software (Berendrecht and Van Geer, 2016; Zaadnoordijk et al., 2019). We modelled the time series of filter 6 of the monitoring well B51E0078 with daily precipitation and evaporation from the nearby weather station 370 Eindhoven of the Royal Dutch Meteorological Institute KNMI as input. The response to evaporation is assumed to be equal to the response of groundwater to precipitation except for a factor. This evaporation factor is an indication of the difference between the actual evaporation and a Makkink evaporation (Obergfell et al., 2019).
We included both the response connected to the seasonal fluctuation of the groundwater head and a much slower response. This way we were able to match the measured heads quite closely (Figure 4.3).

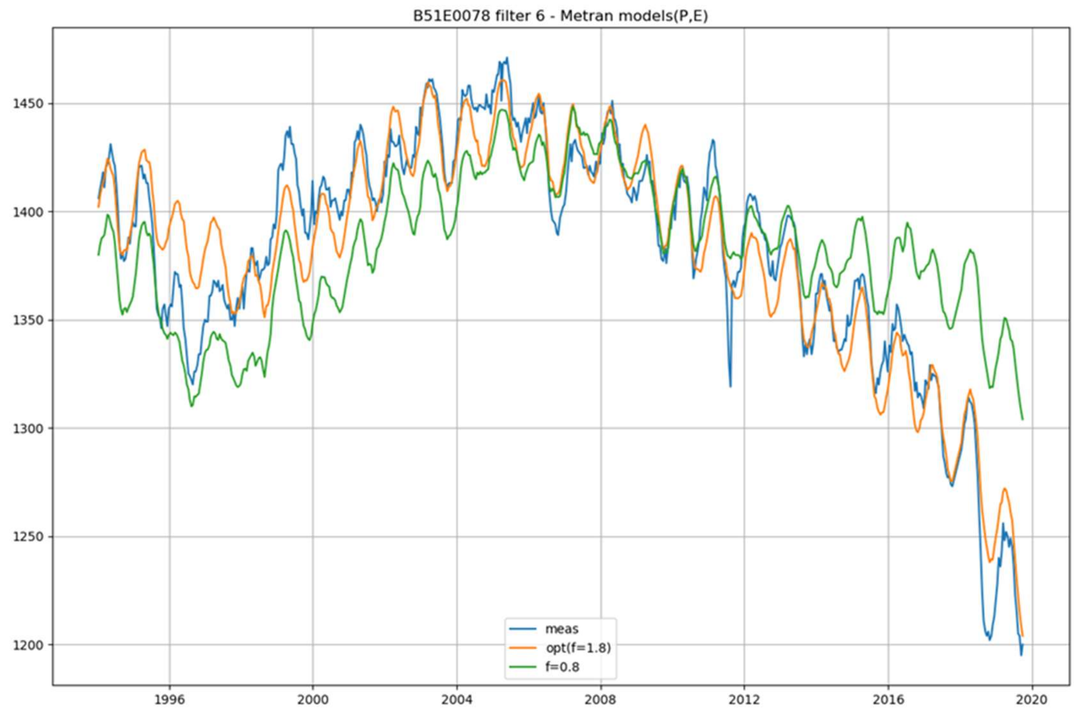

Figure 4.3 Metran modelling of observation well B51E0078. Measured time series in blue, Metran model with exaggerated evaporation (orange) and model with “normal” evaporation (green).

Figure 4.3 shows that the general fluctuation of the deeper heads in the Roer Valley Graben in the time series can be approximated by the Metran model indicated with the orange line using only meteorological fluctuations as input for the transfer-noise model.
However, the evaporation factor in this model has a value of 1.8. It is unlikely that the actual evaporation is this much higher than the Makkink evaporation, which is representative of the evaporation from grassland with optimal soil moisture conditions. A value of 0.8 is more likely (cf. Obergfell et al., 2019). Therefore, a Metran model has

been created in which the evaporation factor was fixed to this value of 0.8 (green line in Figure 4.3).

The general fluctuation of Figure 4.1 is visible in both the green and orange model, indicating that a period of decreasing trends up to 1996, followed by a period of increasing trends between 1996 and 2005, followed by a decrease between 2005 and 2020 can be explained by just using precipitation and evaporation as influences on the groundwater head. This would corroborate our hypothesis that a transformation of only the precipitation and evaporation signals can explain the long-term waves in the groundwater head series of the Roer Valley Graben.

The orange model with the unlikely high evaporation factor performs much better than the green model with the more realistic value. This suggests that the evaporation factor in the orange model does not solely represent the ratio between the actual evaporation and the Makkink evaporation. A possible explanation is that there is another influence on the groundwater system, that *has a similar pattern in time as the evaporation*.

Groundwater abstractions are a candidate. The nearby well field Lieshout of Brabant water does not show much seasonal fluctuation between 1988 and 2012 (

Figure 4.4). So, this is not a likely candidate for this particular monitoring well B51E0078. However, agricultural abstractions may be expected to be strongly correlated with the evaporation and also other abstractions for drinking water and industries like breweries may exhibit similar patterns in time, which are integrated over larger areas in the deeper aquifers of the Roer Valley Graben due to the presence of the aquitards of the combined Peize/Waalre and Kieseloolite Formations.

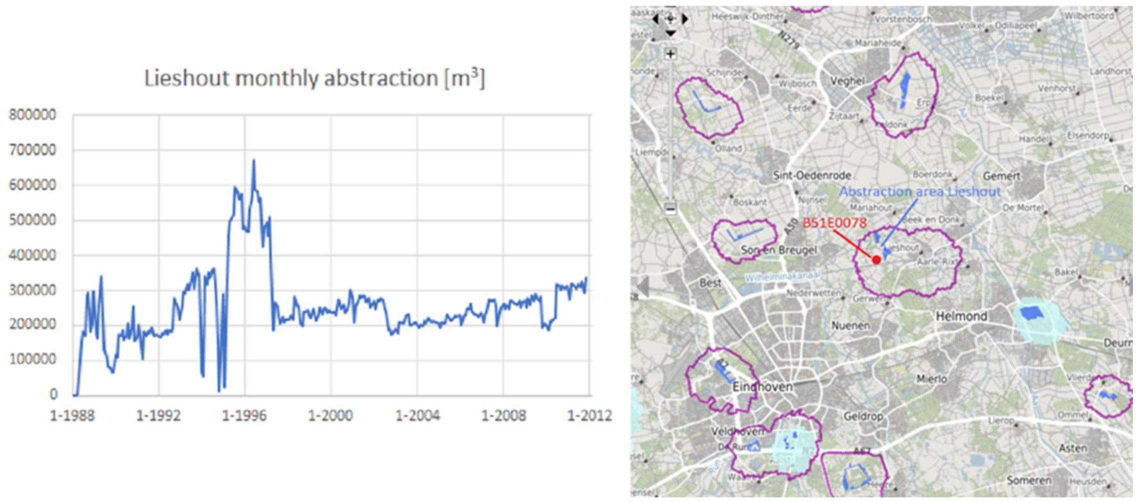

Figure 4.4 Abstraction rate and location of the Lieshout well field.

The connection between abstractions and evaporation suggested by these data-driven Metran models, is used in many physically based groundwater models in the Netherlands (e.g. de Lange et al., 2014). Because exact locations of groundwater irrigation are not known, and there is no viable registration of groundwater abstraction wells for irrigation[1], the modelers seek to find a way to include the effects of irrigation by translating water shortages (the opposite of precipitation surplus) into abstraction rates in their models.

The hypothesis that abstractions with a similar pattern as evaporation, such as for irrigation, have a strong influence on the groundwater head time series in the deeper aquifers of the Roer Valley Graben groundwater system needs further data analysis and conceivably physically based modelling to be verified. One data-driven way forward would be to determine best-fit evaporation factors for many time series in observation wells to see if there are spatial patterns for these best-fit factors. Moreover, known abstraction series of well-registered public supply wells can be screened for signals of seasonal fluctuations in the abstraction rates. If the hypothesis of evaporation-patterns coupled to abstractions would be confirmed, it would be an important finding. For example, irrigation from groundwater is known to have increased since 1976 and especially since the dry years 2003 and 2018, and a further increase of agricultural water demands may be anticipated under the influence of climate change.

[1] Contrary to the situation for registration of irrigation wells in Flanders, see Slenter (2021)

5 SYNTHESIS & OUTLOOK

This report introduced the newest version of the GeoERA Groundwater Viewer which enables cross-border 3D viewing of patterns in groundwater head time series, through some examples of data analysis of groundwater depletion analysis in the H3O-PLUS area. The tool enables the user to assess temporal trends in groundwater heads for individual observation wells, visualizing these trends in maps based on a selected depth interval, in maps based on geological formations and in hydrogeological cross-sections. Similarly, head differences between monitoring screens can be visualized in maps and cross-sections. The updated web viewer now enables to aggregate trends and head differences over areas that the user can select interactively.

The webtool was introduced by analysing trends and head differences in the Roer Valley Graben, which is the main area in the H3O-plus transboundary pilot area of work package 3 in the GeoERA RESOURCE project. Applying the web viewer reveals patterns of temporal trends that indicate a large influence of abstractions for drinking water supply on the head distribution in the main aquifers in the Roer Valley Graben. There is a clear signal of decreasing groundwater heads of 10 cm per year for filters in the deeper part of the Peize/Waalre Formation and the Kieseloolite Formation for the last 15 years. The last 40 years had a more complicated trend pattern of groundwater heads with generally declining trends but a period with stable or increasing heads between 1995 and 2010. This general pattern can be explained by an unexpected long-term response of the groundwater to precipitation and evaporation. Based on the current study, we hypothesize that part of the trend pattern may additionally result from abstractions that follow the pattern of evaporation, such as irrigation during periods of water shortages. Further data-analysis and modelling would be required to further unravel the temporal patterns that were observed in the Roer Valley Graben, importantly as a further increase of water demands for agricultural and human uses may be anticipated under the influence of climate change.

The study demonstrated that head differences between the main deeper aquifers in the Roer Valley Graben and the overlying shallower aquifers have been increasing over the last 30 years. Longer time series that were identified to reveal head differences show that negligible or small head differences existed between the aquifers below the main aquitard in the Roer Valley Graben and the overlying aquifers before the start of the centralized water supply in the 60's and 70's of the last century.

The new webtool helps to quickly unravel such patterns, which are clearly not all well understood. This report demonstrates the new capabilities of the webtool to identify these major influences on the groundwater circulation in the Graben, as the identification of trends and head differences in long time series have now been made more accessible by dedicated selection procedures in the tool. It is our hope that the new webtool may help to improve our understanding of the groundwater circulation in the greater transboundary area of the Roer Valley Graben and support sustainable management of the important fresh-water resource.

6 REFERENCES

Buma, J., and R. Reindersma (2021). Harmonisation of volumes, water balances and recharge and discharge fluxes. GeoERA RESOURCE, Deliverable 3.4.

De Lange, W.J., G.F. Prinsen, J.C. Hoogewoud, A.A. Veldhuizen, J. Verkaik, G.H.P. Oude Essink, P.E.V. van Walsum, J.R. Delsman, J.C. Hunink, H.T.L. Massop, T. Kroon (2014) An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. Environmental Modelling & Software, 59, pages 98-108, doi: 10.1016/j.envsoft.2014.05.009

Obergfell, C., Bakker, M., and Maas, K. (2019) Estimation of average diffuse aquifer recharge using time series modeling of groundwater heads. Water Resources Research, 55. doi: 10.1029/2018WR024235

Slenter, C. (2021) Overview of groundwater management strategies on different sides of common borders. GeoERA RESOURCE, Deliverable 3.6.

Berendrecht, W.L., F.C. van Geer (2016) A dynamic factor modeling framework for analyzing multiple groundwater head series simultaneously, Journal of Hydrology, volume 536, pages 50-60, http://dx.doi.org/10.1016/j.jhydrol.2016.02.028

Zaadnoordijk, W.J., S.A.R. Bus, A. Lourens, W.L. Berendrecht (2019) Automated Time Series Modeling for Piezometers in the National Database of the Netherlands, Groundwater, Vol. 57, No. 6, 834–843, doi: 10.1111/gwat.12819.

Zaadnoordijk, W.J., J. Buma, R. Vernes, K. Beerten, B. Rogiers, C. Slenter, R. Jaritz, B. Linder and H.P. Broers (2021). 3D visualization of cross-border patterns of groundwater depletion. GeoERA RESOURCE, Deliverable 3.5.

Zaadnoordijk, W.J., A. Lourens (2019) Groundwater dynamics in the aquifers of the Netherlands, TNO report TNO 2019 R12031, TNO Geological Survey of the Netherlands, Utrecht, Netherlands.