Stream valley Elperstroom

Modelling the hydrogeological effects of redevelopment of adjacent areas on suitable habitats for alkaline fens and Molinia meadows.

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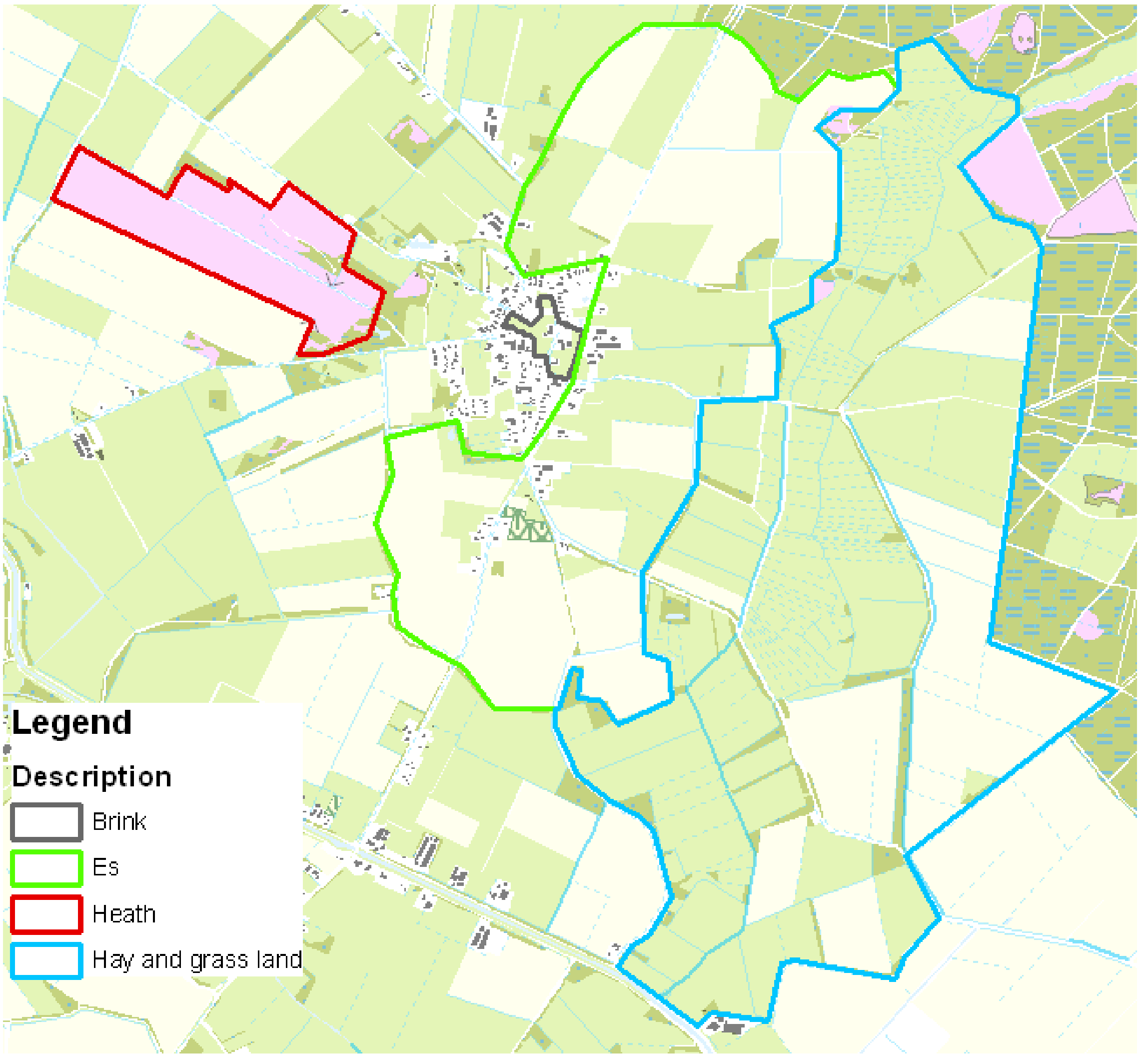
Inhoudsopgave

Appendices

1 Introduction

1.1 Background & problem description

In the High Middle Ages a typical kind of farm village started to develop in the Netherlands. This type of village is in Dutch known as Esdorpen. One of these Esdorpen is Elp, Drenthe shown below.

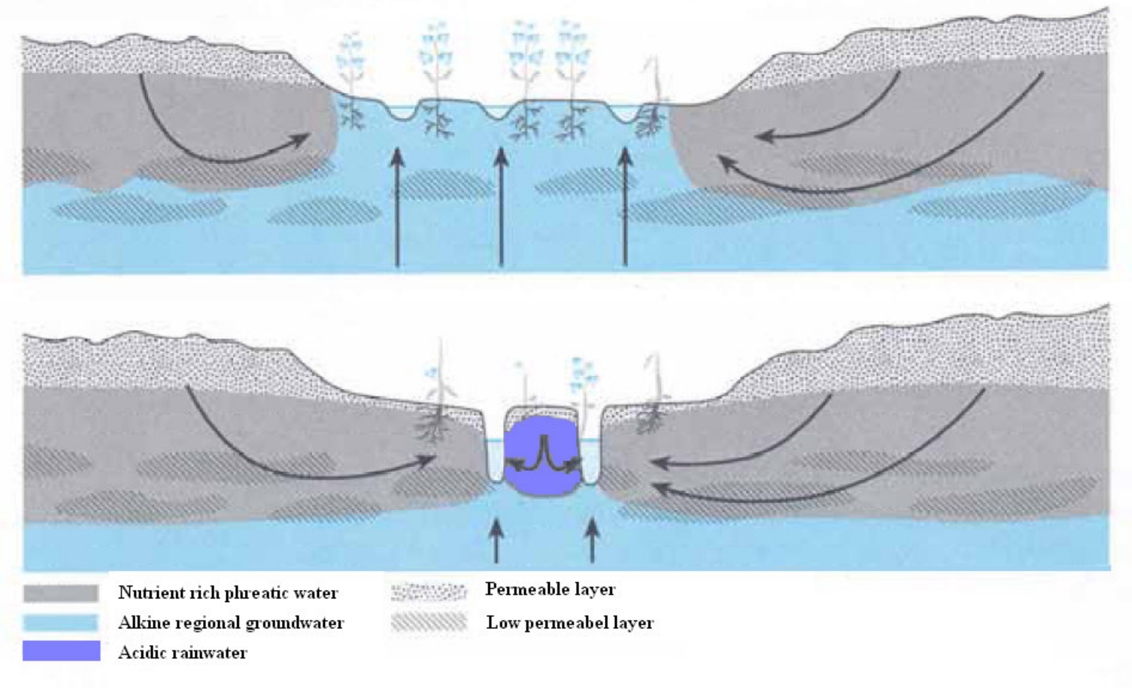


Figuur 1 The Esdorp Elp

In and around this village the typical features of an Esdorp can still be recognized. Firstly outlined in grey; the brink. Originally the brink was on the edge of the village and functioned as place where the cattle could sleep during the night. Outlined in red the heath can be found where the sheep where herder by the village shepherd. Then outlined in green the es, this was a shared agricultural land, where different crops were cultivated. The es was often situated on the higher parts of the area. And last the blue outlined area. This is a stream valley (Elperstroom) with meadows and hay fields. The meadows where used to graze the cows during the day. The fields close to the stream were usually too wet to let the cows graze. These fields were used as hay fields; here the grass was harvested once a year and used as hay for the cattle during the winter.

This type of land use is the basis of the creation of a special habitat type. The annual harvesting of the hay, removes the nutrients which would normally return to the soil. This makes the soil oligotroph i.e. very low levels of nutrients. This effect is strengthened by the low elevation of these areas which causes deep groundwater to seep to the surface. This deep groundwater is low in nutrients. The high pH and dissolved minerals lower the availability of certain nutrients. These conditions are ideal for alkaline fens and Molinia meadows

Over the years, due to more intensified agricultural activities, the area of these habitats shrink and the quality decreases. The problem is described schematically in Figure 2;



Figuur 2 Previous and current groundwater regime in the Elperstroom.

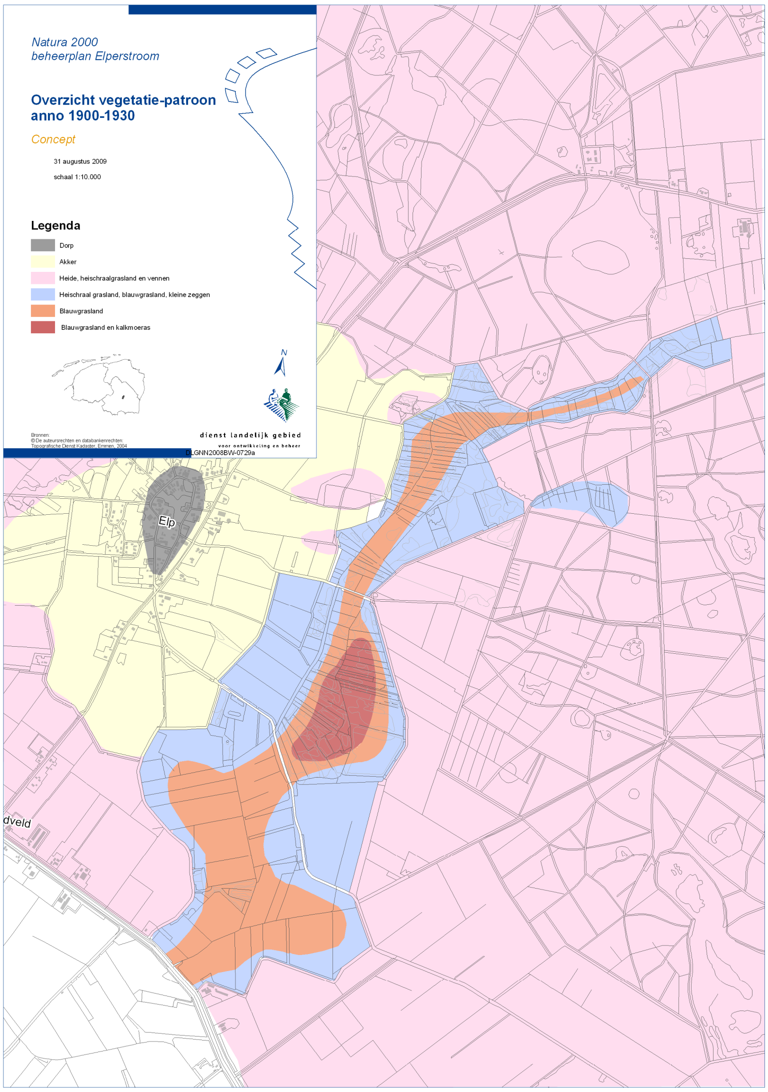
In the past the grasslands were only drained by shallow trenches and streams, see Figure 2. The groundwater in the root zone was manly dominated by upwards seepage from the flanks, which provided the alkaline and oligotrophic conditions favourable for the vegetation.

From around 1900 there is a shift. Due to technological innovations people are able to change the environment to their needs. Where normally the meadows and hay land were too wet for cultivation, a network of waterways could be constructed using new insights and technologies. These networks were then used to drain and discharge water from the area, causing a lowering of the groundwater levels. These lower groundwater levels made the fields useable for cultivation. What was left was a small patch of land close to the stream where groundwater levels could not be lowered any further and could thus not be used for agricultural activities. These areas are surrounded by deep waterways to assure low groundwater levels in the adjacent fields.

In the small patches the deep waterway have a large impact on the upwards seepage. Since the water levels are low, there is a high gradient between the waterway and the phreatic and first confined aquifer. This large gradient causes the upwards seepage to flow to the waterways instead of to the surface and root zone. This has two major effects. First, the groundwater levels will drop, this is effect is strengthened by the drainage to the waterways. Secondly the groundwater will be more rainwater dominated, since rainwater is now the only recharge of groundwater. These processes cause the oligotrophic conditions to change to eutrophic, nutrient rich conditions plus the inflow of water from the strong fertilized adjacent land.

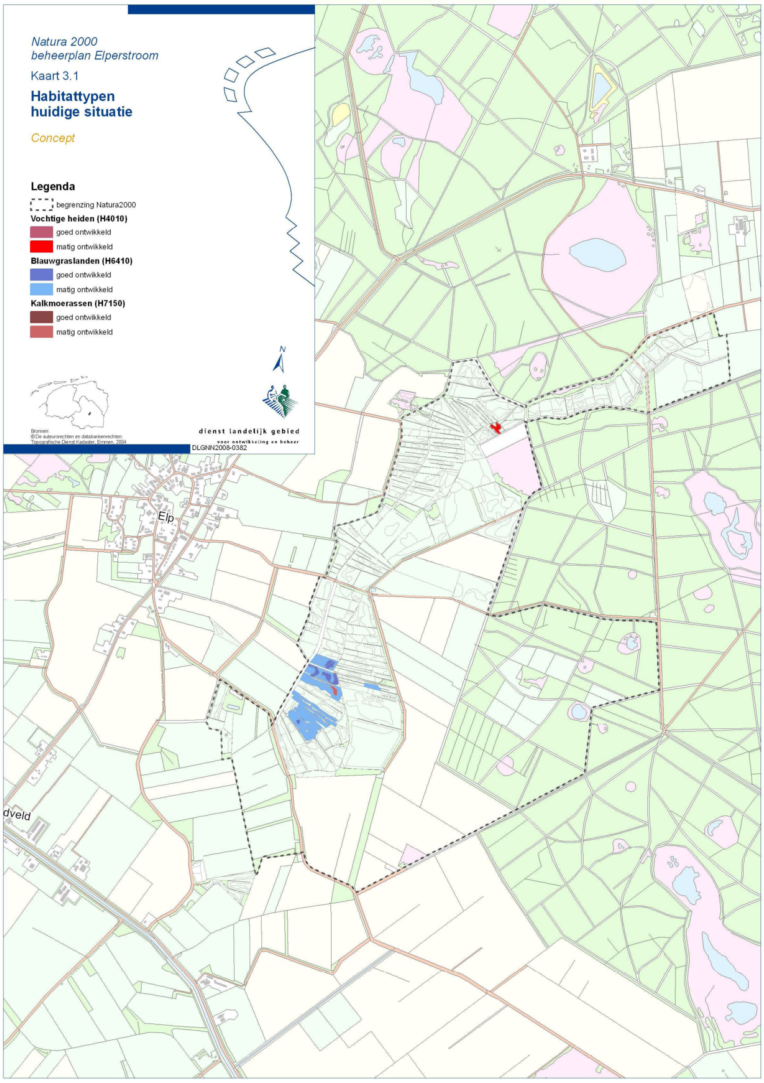
Another process that affects the upward seepage in a negative way is the transformation of heath lands to forest land on the east flank of the Elperstroom. To oppose the large unemployment in the beginning of the 20th century, the government transformed large areas of heath to production forest. This has a large effect on the groundwater recharge, since wood lands evaporate a much larger amount of water then heath. This means that there is less water available for recharge of the groundwater. And since the east flank is a large source of the upwards seepage in the Elperstroom, less groundwater recharge means less upwards seepage

These processes have caused great stress and disappearance of large areas of the alkaline fens and the Molinia meadows over the last century. Where in the past these vegetation types were found in large parts of Drenthe, they are now reduced to a few hectares. This also happened in the Elperstroom;



Figuur 3 Vegetation Elperstroom anno 1900-1930

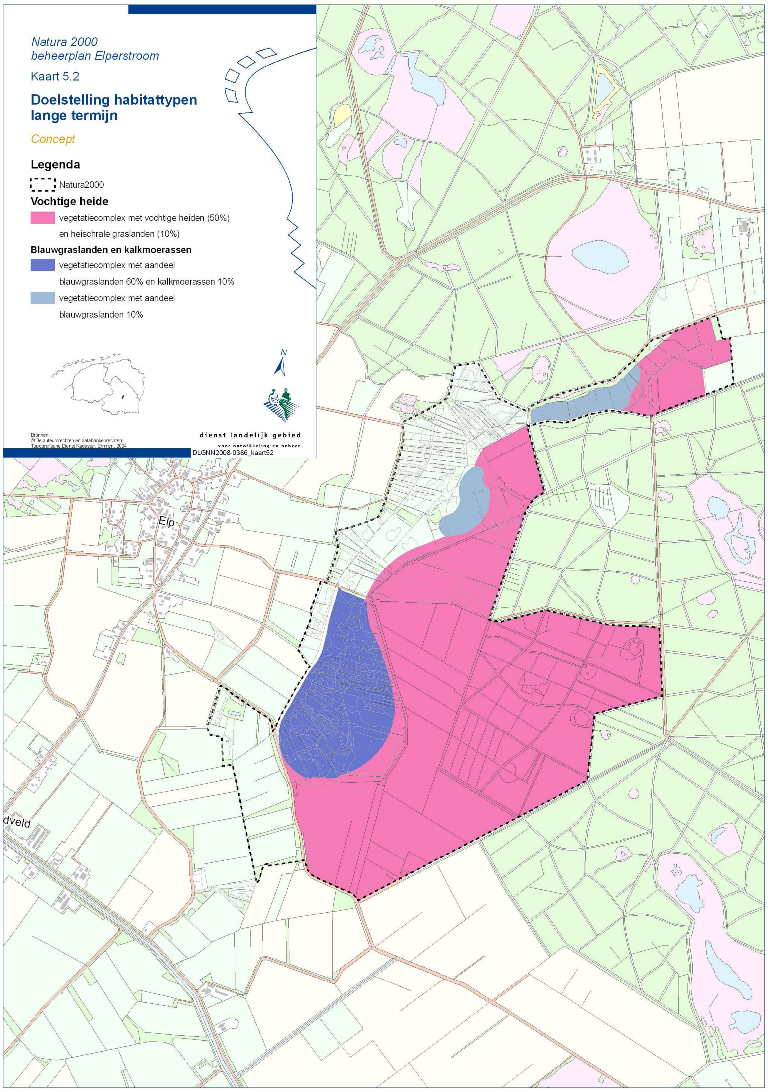
In Figure 3, the vegetation can be seen anno 1900-1930, **(Streefkerk, 1997)**.In that time large areas where covered by heath, shown in pink. On the flanks of the stream the meadows can be seen, in blue. Directly following the stream the Molinia meadows (brown) are found and in the part middle stream the alkaline fens (dark brown). If this is compared to the current situation, some dramatic changes can be seen, **(Bronger, 2000)**;



Figuur 4 Current vegetation situation (2000).

Most of the heath is either changed to agricultural land or woods, not shown in Figure 4. Most of the Molinia meadows are disappeared up to a small patch where most of the vegetation poorly developed (blue and purple). For the alkaline fens the situation even more dramatic, a small patch is left which is poorly developed (brown). This is one of the two places in the Netherlands where this vegetation is found.

The Elperstroom is Natura 2000 area (outlined in black); this means that it is part of an ecological network of protected areas in the European Union. For each of these areas nature goals are established. A nature goal describes which habitat type should be protected and/or restored and in which quantity and quality. In Figure 5 can be seen what the goals are in terms of vegetation;



Figuur 5 Vegatation goals Elperstroom

The goal is Firstly to stop the further decay of the Molinia meadows and alkaline fens and eventually restore a large part (purple and blue). As discussed in this Section; essential for the habitat type is a supply of upwards seepage, this is why hydrogeology is very important in the restore and protection of the alkaline fens and Molinia meadows.

1.2 Motivation

In 2009 a start was made to design a management plan to achieve the nature goals imposed by the Natura 2000. In this context an effort is done to understand and model the hydrogeological situation of the area ***(Schunselaar, 2009)***. During this research it was found that there was too little information to make an accurately calibrated dynamic groundwater model. That is why there was chosen for a stationary model (MICRO-FEM), to get a first insight in what the effect of different management strategies are. In the design management plan was decided that an effort would be made to further improve the knowledge of the geology and hydrology of the area. This knowledge can then be used to make a dynamic model of the area, to get better insight in the seasonal effects of different strategies. The next version of the management plan is planned in 2017. In this Thesis, in anticipation to the new management plan, an effort will be done to make a dynamic model of the area, with the information that is now available.

1.3 Research goal & method

As mentioned, the focus of the Thesis will be on the protection and restoration of the upwards seepage to the Elperstroom. More specific on the upwards seepage to the Reitma, this is the middle part of the Elperstroom, approximately the purple part in Figure 5.

Firstly, an inventory will be made of the current hydro(geo)logical situation. This will be done using monitoring wells and information provided by the water board. Secondly, using this information combined with a large number of boreholes the hydrogeological model (MIPWA) will be validated and further calibrated. The resulting model will then be used to calculate the effects of different water management strategies. Concluding, the objectives are;

- To give insight in the effects of different management strategies on the upwards seepage in the Reitma.
- Collect all the available information of the area, geological and hydrological.
- Get insight in the current situation of the upwards seepage.

1.4 Research questions

The following research questions will be addressed in the Thesis;

- What can be said about the current hydrogeological situation, regarding upwards seepage and groundwater levels?
- Using a MIPWA model what can be said about the effects and efficiency of different management scenarios?

1.5 Thesis outline

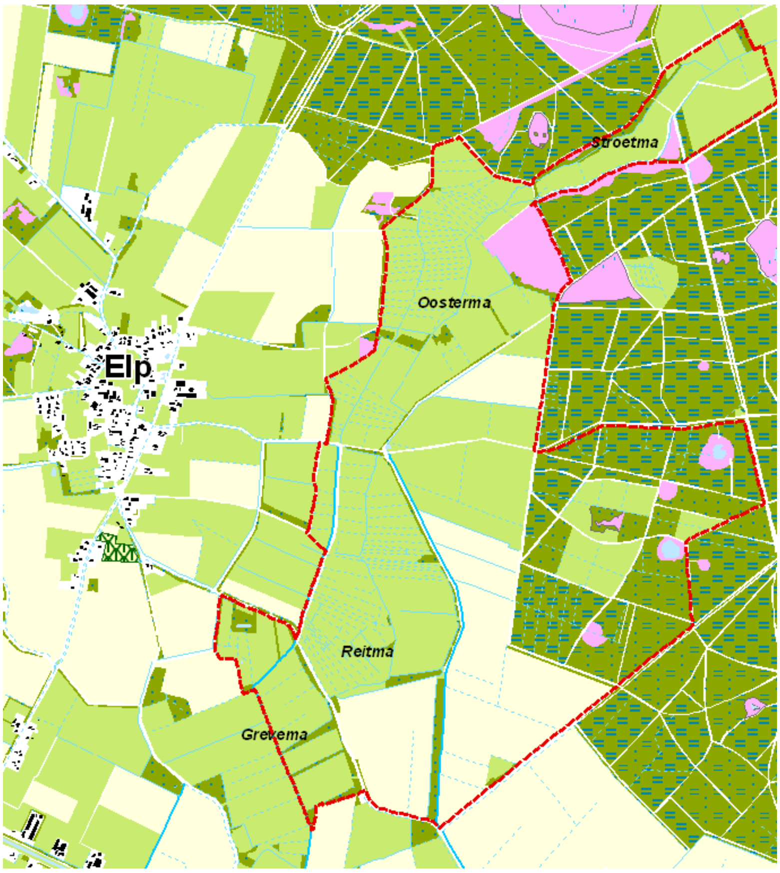
In Chapter two the study area is discussed. In addition the location, habitat types, geology, current hydrological situation, hydrochemistry and the upwards seepage will be discussed. Next in Chapter three, the theory of the MIPWA model will be discussed. In Chapter 4 there will be discussed how the study area is currently modelled in MIPWA. How this is improved and using available data and local knowledge of the area is addressed in Chapter 5. In Chapter 6 different management scenarios and there effects according to the model will be discussed. To conclude in Chapter 7 there is a conclusion and discussion of the results of the Thesis.

2 Study area

2.1 De Elperstroom

As mentionend in Chapter 1 the Elperstroom is part of the formal esdrop; Elp, The Netherlands. The Elperstroom is situated in the middle of the province of Drenthe, Figure 6.If we zoom in to the Elperstoom, Figure 7;

Figuur 6 Location of Elp



Figuur 7 The Elperstroom

It can be seen that the Elperstroom consists of 4 parts; Stroetma, Oosterma, Reitma and Grevema. The Elperstroom starts in the Stroetma and ends up in the Grevema where a pumping station pumps it in the Oranje kanaal. In this research the focus will be mainly on the Reitma, where the most valuable vegetation exists.

2.2 Habitat types

In the Reitma two habitat types can be distinguished as described by Natura 2000, **(EEA ,2000)** namely;

- **Molinia meadows on calcareous, peaty or clayey-silt-laden soils (H6410)**
- **Alkaline fens (H7230)**

Firstly the Molinia meadows, during the winter and early spring this habitat type requires a high groundwater level near the surface. During the summer the levels drop, however there is a critical level to which it can drop namely a mean lowest level of 80 cm. The acidity of the groundwater favourable by the flora in this habitat type is basic. The supply of upwards seepage should be more then 1 mm/day averaged over a year. This is important because it provides basic and nutrient poor conditions. The seepage must once or twice reach the root zone, in the summer when the groundwater levels are lower capillary rise should provide the supply basic and nutrient poor groundwater. The nutrient levels area another important criteria, the favourable conditions are nutrient poor.

The alkaline fens require a mean groundwater level during the spring of 5 cm above and 10 cm below surface level. During the summer the groundwater levels should not drop to more then 30 cm beneath surface level. The groundwater should have a pH between 5.5 and 7.0 and nutrient poor. To assure these conditions the upwards seepage should have a year average of 2 mm/day.

2.3 Geology

In this Section the geology of the study area will be discussed. This Section is manly based on the data found in REGIS II. The different formations will be discusses in order from the hydrogeological basis to the surface.

2.3.1 Breda formation

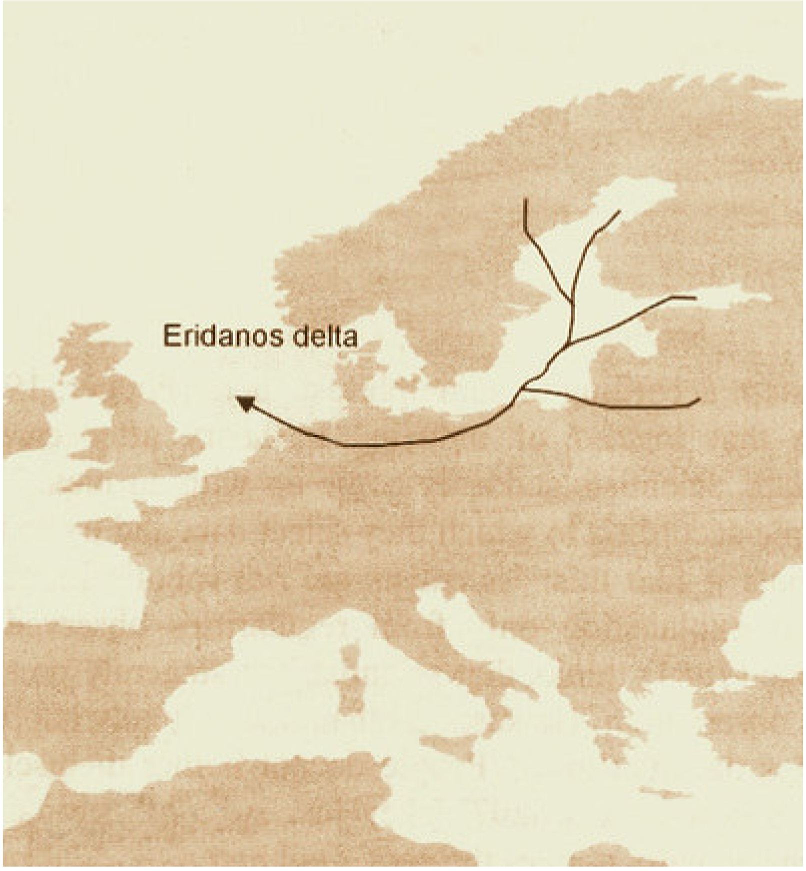
The hydrogeological base is formed by the formation of Breda. This is a formation that is formed under shallow marine en coastal conditions in the Miocene (23 to 5 million years ago). During the Miocene the Netherlands was covered with a shallow sea, in this sea glauconite holding sandy clay was deposited. The formation has a thickness between 60 and 160 meters and the basis of the formation varies between -150 and -100 mNAP.

2.3.2 Oosterhout formation

On top of the formation of Breda, the formation of Oosterhout is found. This formation is formed under the same conditions as the formation of Breda, but in a later stage, the Pliocene 5.3 to 2.6 million years ago. The dominant lithography is very fine to coarse sand $(105-420\mu m)$. The basis is around -150 mNAP and the top -100 mNAP

2.3.3 Peize formation

The next formation is the Peize formation. This formation manly consists of fluvial sediments carried by the Eridanos. The Eridanos, also known as the Baltic river, is a former river which ran from where now the Baltic Sea is;



Figuur 8 The Eridanos delta in the Pliocene

The delta of the river was formed by the whole north western European lowlands. The formation was formed from 3.6 to 1.2 million years ago. It manly consist of coarse to very coarse sands $(200 - 2000\mu m)$. In the study area the basis is found at -100 mNAP and has an average thickness of 40 m.

2.3.4 Appelscha formation

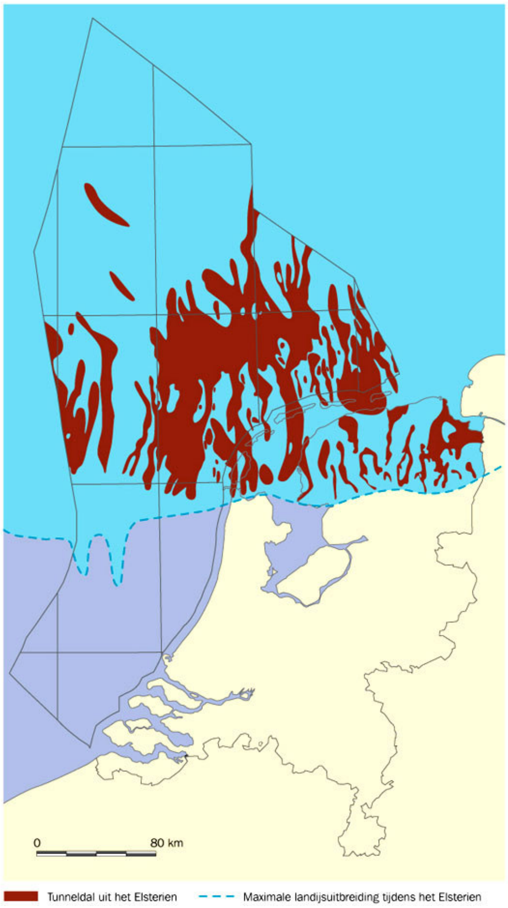
Like the Peize formation, the Appelscha formed from fluvial sediments of the Eridanos. However the source of the Eridanos shifted from the Baltic sea to the Thüringer Walt and the Erzgebirge. This shift was caused by the glaciations of the Menapien, 1 to 1.2 million years ago. The formation manly consist of coarse to very coarse sands $(150 - 2000\mu m)$. The basis of the formation can be found at -50 mNAP and the average thickness is 20m

2.3.5 Urk formation

The Urk formation is formed 456 to 850 thousand years ago. It is a fluvial deposition of the Rhine which in that time had it's delta in the north of the Netherlands. The formation is known for it's very coarse sands and even gravel $(2 - 63mm)$. The sands are also calcium rich, which is of importance for the vegetation in the Elperstroom. The formation has a thickness of 10m in the south and 20m in the north of the study area. The bases varies between -13 and -30 mNAP.

2.3.6 Peelo formation

The Peelo formation is formed during and just after the glaciations of the Elsterien, between 465 and 418 years ago. The formation is found in deep gullies, so called tunnel valleys. These valleys are formed during the Elsterien under the glaciers. Short after the melting of the glaciers the tunnel valleys are filled with fluvioglacial sediments forming the Peelo formation.



Figuur 9 Location of the tunnel valleys of the Elestrien

The tunnel valleys can cut through the older formation even down to the Breda formation. In the study area only a cut down to the Peize formation is found. The formation consists of very fine to fine sands. The average basis is found at -10 mNAP and the thickness varies between 13 and 3 meter. According to REGIS II there is also clay layer of this formation present in the study area, however there are no boreholes found in the area which support this.

2.3.7 Drenthe formation

The Drenthe formation is mainly found on the flanks of the Elperstroom. The formation declines at both the east and west flank, with a steepness up to 4%. The formation is formed during the glaciations of the Netherlands during the Saalien, 238 to 128 thousand years ago. The formation is a moraine, meaning that the sediments were transported by the glaciers and left behind during melting. The sediment is also known as boulder clay (keileem). Boulder clay is known to be poorly sorted and mainly consist of sandy loam, sporadically gravel and even boulders are found. Often boulder clay is rich in lime and has a low permeability for water.

2.3.8 Boxtel formation

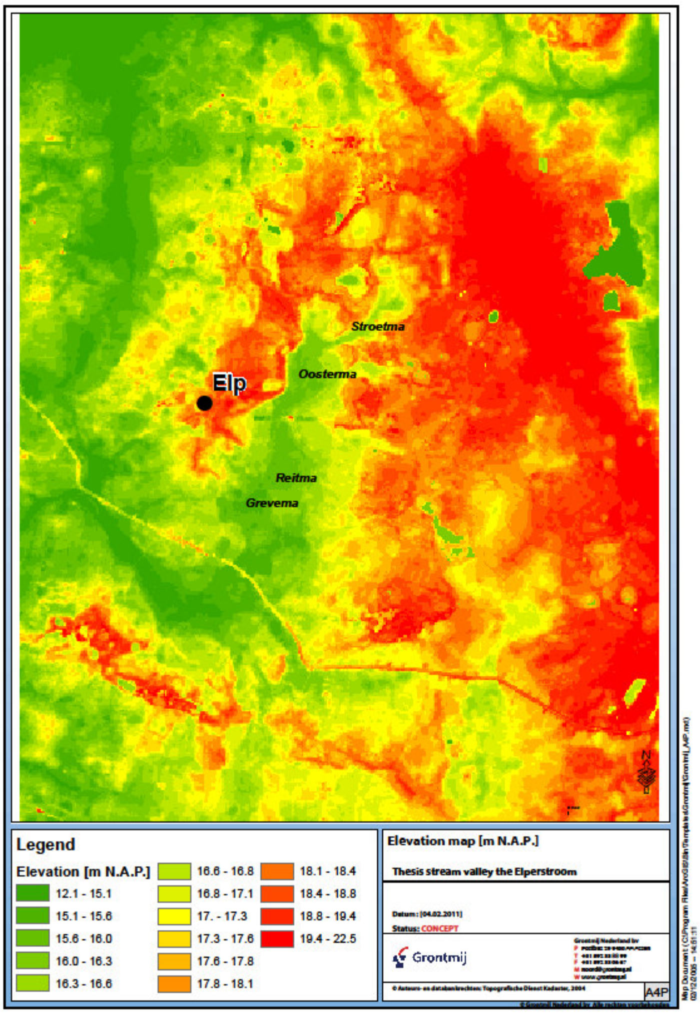
This formation is formed between 166 and 11 thousand years ago. It manly consists of aeolian sands i.e. sands formed under influence of the wind. In this sand loamy layers can be found, which are formed during flooding of small streams.

2.3.9 Holocene sediment

Since the Elperstroom is a valley and thus the elevation is lower then the surroundings there will be upwards seepage in this area. Because the upwards seepage passes through lime rich layers the groundwater will be alkaline buffered. These are the ideal conditions for peat to form. In the Elperstroom almost everywhere shallow peat layers are found.

2.3.10 Elevation

The geological processes discussed can directly be seen in the elevation map of the Elperstroom. In the east a large elevated ridge can be seen, the Hondsrug. This is a moraine formed during the glaciations. On this ridge different streams origin, top right and left of the ridge, and the lower left and in the middle left the Elperstroom, Figure 10;



Figuur 10 Elevation map Elperstroom [m N.A.P.]

It can be seen that it has cut trough the boulder clay to form a stream valley and depositing clay during this process, boxtel clay. The stream starts at an elevation 17.50 m N.A.P. and ends up at the Oranje kanaal at an elevation of 15.50 m N.A.P. It can also be seen that originally, before the construction of the Oranje kanaal (1850), the Elperstroom streamed to the south west. Here it was connected to westerborker diep and would eventually end up in the IJselmeer.

2.4 Surface water

A map of the surface water in the area of the Elperstroom can be found in Figure II.8. It can be seen that in the Reitma there are a lot of small trenches to drain the rainwater quickly from the area. To the west of the Reitma the former Elperstroom can be seen which is channelized to assure good drainage of the agricultural lands. To the east a similar channel can be seen. To manage different groundwater levels weirs are installed in the waterways to control the water levels and thus indirectly the groundwater levels. In the Reitma the weir is set to 15.3 – 15.4 m N.A.P., were normally the low level occurs in the summer and the high in the winter.

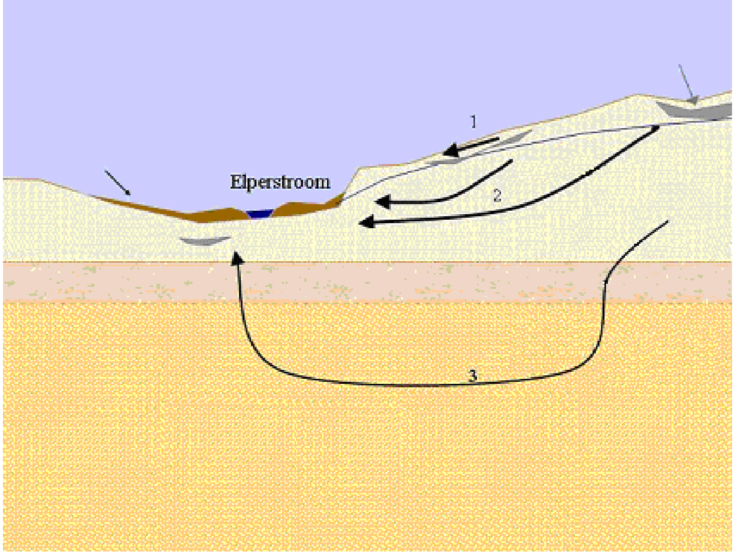
Figuur 11 Weir Reitma

To the north, Oosterma, the levels are set to 15.5-15.7 m N.A.P. The levels in the agricultural lands to the west and east are respectively, 15.4-15.5 and 15.15-15.65 m N.A.P. To the south of the Reitma, Grevema, a large agricultural area can be seen with a system of waterways to ensure a low groundwater level. The water levels are managed at 14.5-14.8. This causes a high difference between the the Reitma and Grevema of 80 cm in the summer and 60 cm in the winter.

The past 10 years many adjustments are made to the water system in and around the Elperstroom. Goal was to restore the natural water system and undo the agricultural “improvements” of deep canals that drain the groundwater system. Many of the main water courses are filled and replaced by shallow streams and ditches.

2.5 Groundwater

The groundwater flow to the Reitma can roughly be divided in to three systems. The first one is the shallow one, precipitation infiltrates locally in the area. From here it will flow phreaticcally, partly over boulder clay, to the lower parts and trenches, denoted as 1 in Figure 12.

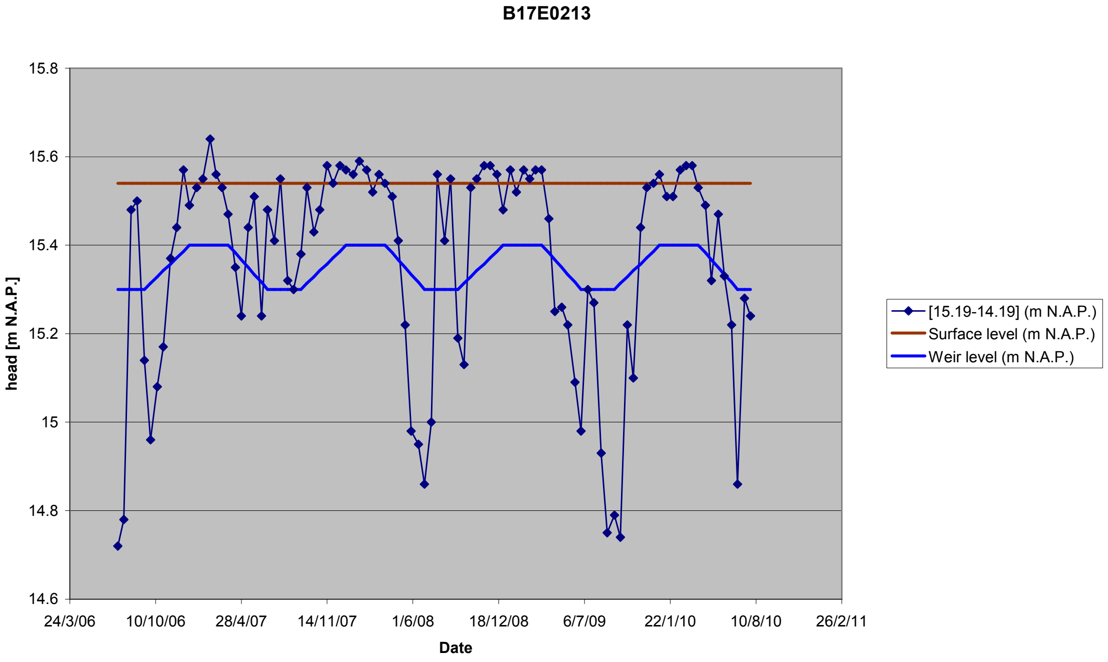


Figuur 12 Groundwater flow in a cross Section of the Elperstroom ***(Schunselaar, 2009)***

The second is the deep system; here precipitation which infiltrates higher on the east flanks will infiltrate down to the first aquifer, Peelo sand. Then it will flow partly to the valley where is will seep upwards to the surface.

The third system is the regional flow; part of the ground water that infiltrates on the flanks will end up in the deeper aquifers, Urk formation. From here it flows to the Elperstroom where a part can come to the surface as upwards seepage. Another part flows underneath towards the Grevema. This route is considerably longer then the shallow ones, since it passes through several confining layers. Since Urk sands are considered to be calcareous, mineral enrichment of the groundwater/ upwards seepage will largely take place through the regional flow.

In Figure 13 below a time series of a monitoring well which is typical for the Reitma can be seen;

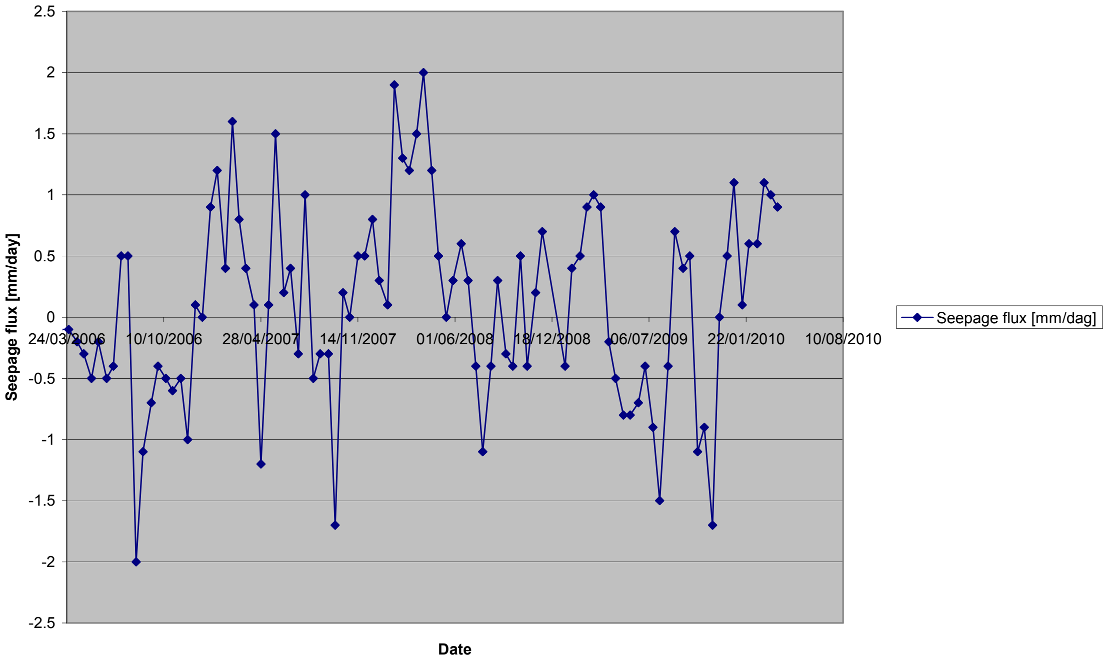


Figuur 13 Monitoring well in the middle of the Reitma, monitoring well B17E0213

It can be seen that during the winter there is a period in which the groundwater levels are above surface level (inundation). During the summer however, ground water levels can drop as far as 1 m beneath surface level. A statistical analysis was made calculating the mean, mean based on the three lowest values of each year, MLGL and mean based on three highest values of each year, MHGL;

Statistics	Head [m N.A.P.]
Mean	15.4
MHGL	15.6
MLGL	15.0
Dynamics	0.6

In the graph below the upwards seepage to the first layer measured in a monitoring well in the Reitma is shown;



It can be seen that the there are periods where there is upwards seepage and periods were the water infiltrates. The mean upwards seepage is for this monitoring well is 0.1 mm/day.

2.6 Hydrochemistry

During the journey of groundwater through the subsurface; the chemical composition of the groundwater will change. The composition is mainly influenced by the chemical condition in the subsurface. In the coming Section there will be discussed how this composition changes, from the infiltration of rainwater to upwards seepage in de Reitma.

Since rainwater is merely evaporated water one would expect that there are no dissolved substances in it and has a pH of seven. However, during the journey through the atmosphere rainwater can collect different gasses, ions and other substances. De pH is mainly determined by the amount of dissolved carbon dioxide which forms carbonic acid. Beside this natural present gas, also gasses due to human actions are dissolved, NOx, NHx and SOx. Even though the concentrations of the latter are decreasing in recent years, they still increase the acidity of the rainwater. The mean pH of rainwater is around 5.1, moderately acid.

When excess precipitation starts to infiltrate it will first reach the unsaturated zone. In the unsaturated zone the pores are partly filled with water and partly with air, the soil is often rich in organic materials. Large part of this organic material will be digested by micro organism leaving behind the minerals, mineralization. During this process oxygen is consumed and carbon dioxide and nutrients such as sulphate, ammonium and phosphate are produced. Another process is cation exchange; here cations (positively charged atoms or molecules) in the groundwater are exchanged with cations adsorpted by the soil. This exchange is mainly between protons in the groundwater and magnesium and calcium in the soil, this process will increase the pH. If during infiltration the water passes through a peat layer, this process will be even stronger due to the large amount of adsorpted cations in peat. In a research of (Meinardi, 1980), there was found that when groundwater infiltrated through peat, the concentrations bicarbonate, carbon dioxide, calcium, ammonium, iron and manganese increased. Part of the water will infiltrate to the saturated zone and part will runoff to surface water or come to the surface in lower parts. It can be concluded that the unsaturated zone causes the infiltrating rainwater to take up nutrients, eutrophication.

In the unsaturated zone due to respiration, the oxygen concentrations will decrease whereas the carbon dioxide, proton, nitrate and sulphate concentrations will increase. Because of this naturally present calcium carbonate in the Urk formation will be dissolved. This will increase the calcium concentration and decrease the carbon dioxide concentration. This will in turn increase the pH of the groundwater. When the groundwater infiltrates deeper and deeper the oxygen concentration will decrease more and more due to micro biological influences. This process goes on until anaerobic conditions are reached. When this happens the next best electron acceptors will be used, respectively; nitrate, iron(III), sulphate and carbon dioxide. This causes that the nitrate and sulphate concentrations decrease and that iron will dissolve in the groundwater. This means that the overall concentration of nutrients decreases.

The residence time of groundwater in the saturated zone is usually in the order of 10 year and for the deep groundwater even 100 year. So when groundwater reaches the surface again in the form of upwards seepage, it will be anaerobic with low concentrations of nutrients and high concentrations of dissolved iron and calcium and a pH around 7 or 8. The iron and calcium lower the availability of nutrients such as nitrogen and phosphor to the plants. This is because the iron and calcium bind stronger to the soil then most nutrients. Since plants take up nutrients directly from the soil, there will be less available for plants in areas with upwards seepage. So areas with iron and calcium rich upwards seepage will have a non eutrophic character. Another characteristic feature for these areas is the presence of red precipitation of iron hydroxides. These form when the anaerobic iron rich groundwater comes in contact with oxygen, either in phreatic groundwater, directly from the atmosphere or in surface water. The red precipitation is usually accompanied by iron reducing bacteria, which can be seen in the form of an oil film, Figure 14.

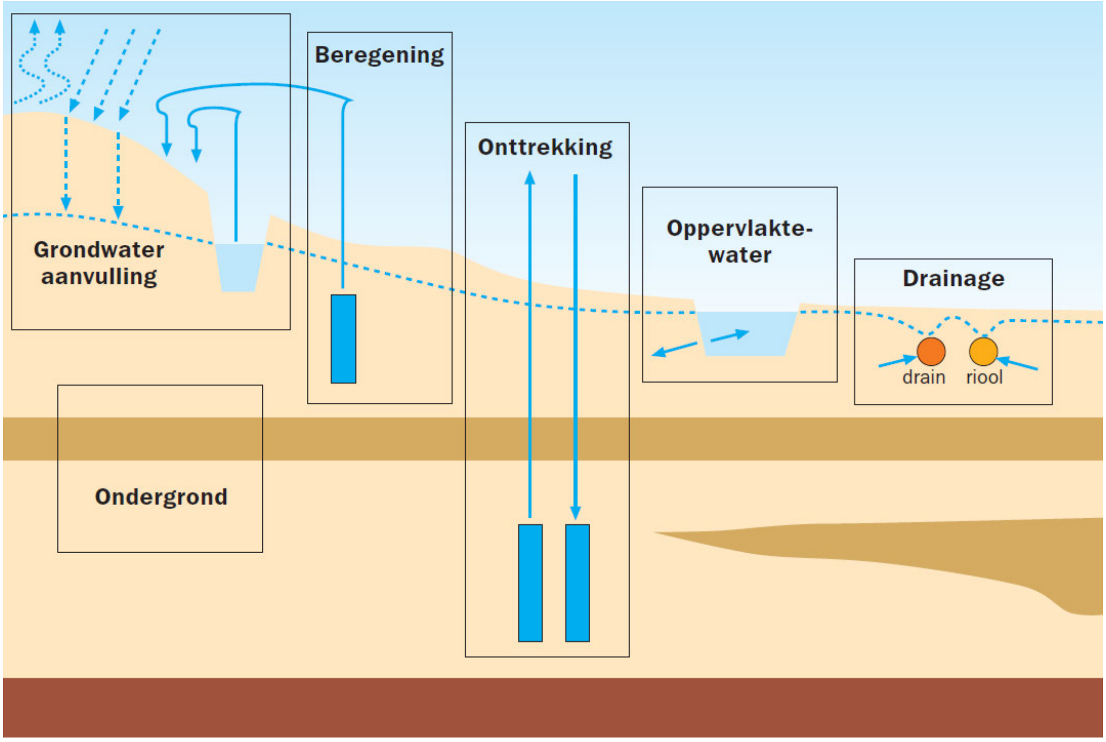
Figuur 14 Precipitation of iron oxides with an oil film of iron reducing bacteria, Reitma.

As discussed due to external effects the upwards seepage in the Reitma is decreased over the years, Figure 2. This caused the groundwater levels to drop and the area became more rainwater dominated, which in turn affect the groundwater chemistry. This causes the soil to become increasingly more aerobic and acidic. In large part of the Reitma there are peat layers present. In de past mineralization of these layer was minimal due to the anaerobic conditions. Now, due to the disappearance of the anaerobic upwards seepage, the peat will start to mineralize. In this process more and more nutrients are created. Since the supply of iron is also decreased, more nutrients are directly available for vegetation. Since rainwater has a lower pH then the upwards seepage, the soil will become more acidic. The mineralization of peat will also make the soil more acidic. Unfortunately these are exact the conditions that are unfavourable for the habitat types in the Reitma.

3 Theory groundwater model MIPWA

3.1 MIPWA

Since 1998 the provinces of the Netherlands determine the desirable ground and surface water regime (GGOR, “Gewenste Grond- en Oppervlakte Regime”) **(4e waternota, 1998)**. To help determine this, a consortium of; TNO, Alterra, Royal Haskoning and Tauw, commissioned by the northern water managers developed a modelling instrument. This instrument is known as MIPWA (“Methodiekontwikkeling voor Interactieve Planvorming ten behoeve van Waterbeheer”). MIPWA is a detailed groundwater model of the northern part of the Netherlands; it covers a million hectares in a resolution of 25 by 25 meter. In Figure 15 below it can be seen which groundwater related processes are modelled.



Figuur 15 Processes in MIPWA **(TNO, 1998)**

To model the groundwater process MIPWA makes use of MODFLOW. The MODFLOW code uses the finite difference method to solve the groundwater flow equation. This equation is a partial differential equation;

$$\frac{\partial}{\partial x}\left[k_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_{zz}\frac{\partial h}{\partial z}\right]+W=S_s\frac{\partial h}{\partial t}$$

Equation 1

Were h is the head in $[m]$, k_{xx}, k_{yy}, k_{zz} the hydraulic conductivity in the x, y, z-direction in $\left[{}^{m}\!/\!{}_{day}\right]$, x, y, z are the spatial coordinates in $[m]$ and t the temporal coordinate in $[day]$. Further S_s is the specific storage in $\left[m^{-1}\right]$ and W the volumetric flow rate per unit volume representing sinks and sources in $\left[day^{-1}\right]$, with $W > 0$ representing a source and $W < 0$ a sink. This equation is derived by computing a volume balance for a small representative elemental volume and the Darcy's law;

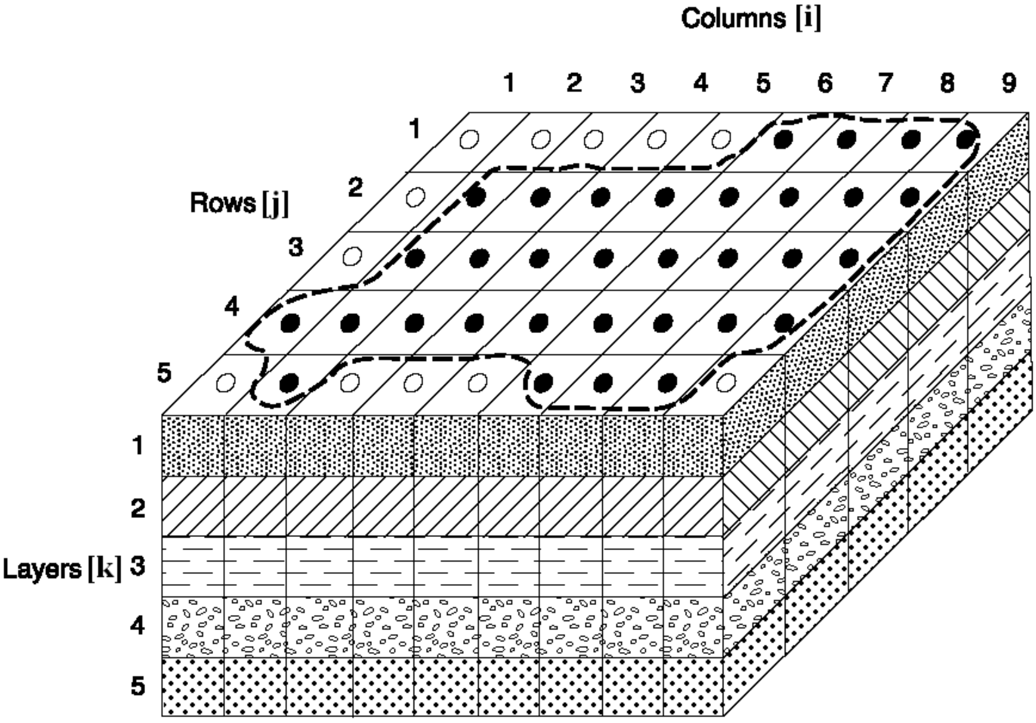
$$q_x = -k_{xx} \frac{\partial h}{\partial x}, q_y = -k_{yy} \frac{\partial h}{\partial y}, q_y = -k_{zz} \frac{\partial h}{\partial z}$$

Equation 2

Were q_x, q_y, q_y are the fluxes in respectively the x,y,z direction. For the groundwater flow equation few analytical solutions are known and only of simplified versions assuming isotropic, homogenous or other simplifying conditions. In reality the subsurface has a capricious nature; using simplifications can then result in big differences between calculated results and reality. Since in the management of nature reserves small effects can make a big difference it is necessary to solve the full groundwater flow equation. To do this the groundwater system is discretized, instead of solving the equation for the whole system and every timestep, it is solved for discrete times and discrete points in the system. This means that the groundwater system and equation has to be transformed to a discrete system and equation. In the upcoming Sections there will be explained how MODFLOW does this. Firstly the schematisation of the subsurface will be discussed and then transformation of the equation, parameters and boundary conditions will be discussed in the last Section.

3.2 Schematisation

To transform the subsurface to a discrete set, the whole groundwater system is divided into small cells;



Figuur 16 MIPWA schematisation

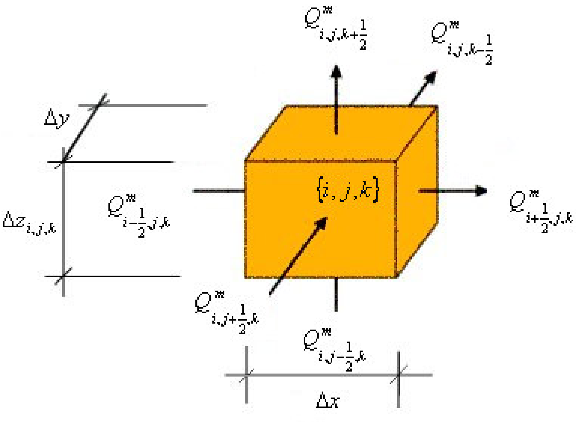
In each of these cells all the parameters are assumed to be constant. In the centre of the cell a point is defined, the nodal point, for which the head is calculated. The coordinates of the cell are given as i, j, k they are respectively the column, row, layer number. First the groundwater system is divided in layers, in the vertical direction;

Figuur 17 Model layers

These layers correspond with the aquifers and aquitards. In MIPWA the schematization is quasi 3D meaning that there are only cells in the aquifers and no cells in the aquitards. It can be shown that to calculate the correct head in an aquitard, the aquitard needs to be subdivided in separate layers again, this due to numerical error. This would mean a significant increase in computing time. Instead an extra term is added to the vertical conductivity, this will be shown in the next Section. The height of each cell is chosen equal to the height of the aquifer. In the horizontal direction the schematization is more trivial, the width and length are simply chosen constant and equal to $25m$. So each cell has the dimensions $\Delta x, \Delta y, \Delta z_{i,j,k}$ in meters. In the next Chapter will be explained where each geological formation is schematizatised.

3.3 Discrete equation

To derive the discrete equation we start with computing the mass balance of cell $\{i, j, k\}$;



Figuur 18 Mass balance

If we add all the fluxes we find;

$$Q^m_{i-\frac{1}{2},j,k}+Q^m_{i+\frac{1}{2},j,k}+Q^m_{i,j-\frac{1}{2},k}+Q^m_{i,j+\frac{1}{2},k}+Q^m_{i,j,k-\frac{1}{2}}+Q^m_{i,j,k+\frac{1}{2}}+W^m_{i,j,k}=S^s_{i,j,k}\Delta x\Delta y\Delta z_{i,j,k}\frac{h^m_{i,j,k}-h^{m-1}_{i,j,k}}{\Delta t}$$

Equation 3

,were $Q^m_{i-\frac{1}{2},j,k}, Q^m_{i+\frac{1}{2},j,k}, Q^m_{i,j-\frac{1}{2},k}, Q^m_{i,j+\frac{1}{2},k}, Q^m_{i,j,k-\frac{1}{2}}, Q^m_{i,j,k+\frac{1}{2}}$ are the flow fluxes in $\left[L^3/T\right]$ trough the different cell faces, $W_{i,j,k}$ the volume flux of all the sources and sinks added together in $\left[L^3/T\right]$. Further $S^s_{i,j,k}$ is the specific storage in $\left[L^{-1}\right]$, $h^m_{i,j,k}, h^{m-1}_{i,j,k}$ are respectively the current and past head in the cell in $[L]$ and Δt the length of the time step in $[T]$. It should be noted that all parameters with an index m are different each time step. In MODFLOW the forward difference method is used, it is forward in the sense that all the fluxes used in calculation are in the same time step as the head that has to be calculated, $h^m_{i,j,k}$.

The next step is to further specify the fluxes. Firstly the sources and sinks, there is chosen to use linearize the sources and sinks. This means that the sources and sinks are up to a constant linear depended on $h^m_{i,j,k}$. This makes;

$$W_{i,j,k}=P^m_{i,j,k}h^m_{i,j,k}+Q^m_{i,j,k}$$

Equation 4

With the constants $P^m_{i,j,k}$ in $\left[L^2T^{-1}\right]$ en $Q^m_{i,j,k}$ in $\left[L^3T^{-1}\right]$. Depending on the process modelled the constant will be different, this will be further specified in the upcoming Sections. The other fluxes are groundwater flow related and thus described by Darcy's law. As an example the flux through the left face;

$$Q^m_{i-\frac{1}{2},j,k}=-k^h_{i-\frac{1}{2},j,k}\Delta y\Delta z_{i,j,k}\frac{h^m_{i-1,j,k}-h^m_{i,j,k}}{x_{i-1,j,k}-x_{i,j,k}}=-C_{i-\frac{1}{2},j,k}\left(h^m_{i-1,j,k}-h^m_{i,j,k}\right)$$

Equation 5

Here $k^h_{i-\frac{1}{2},j,k}$ is the horizontal hydraulic conductivity in $\left[LT^{-1}\right]$ and $C_{i-\frac{1}{2},j,k}$ the hydraulic conductance in $\left[L^2T^{-1}\right]$ which is given by;

$$C_{i-\frac{1}{2},j,k}=\frac{k^h_{i-\frac{1}{2},j,k}\Delta y\Delta z_{i,j,k}}{x_{i-1,j,k}-x_{i,j,k}}=\frac{K^d_{i-\frac{1}{2},j,k}\Delta y}{x_{i-1,j,k}-x_{i,j,k}}$$

Equation 6

.

Were $K^d_{i-\frac{1}{2},j,k}$ is the transmissivity in $\left[LT^{-1}\right]$ which is the hydraulic conductivity multiplied by the thickness of the aquifer. Similar equations can be derived for the other faces making;

$$\begin{aligned}
&C_{i,j-\frac{1}{2},k}\left(h^{m}_{i,j-1,k}-h^{m}_{i,j,k}\right)+C_{i,j+\frac{1}{2},k}\left(h^{m}_{i,j+1,k}-h^{m}_{i,j,k}\right)\\
&+C_{i-\frac{1}{2},j,k}\left(h^{m}_{i-1,j,k}-h^{m}_{i,j,k}\right)+C_{i+\frac{1}{2},j,k}\left(h^{m}_{i+1,j,k}-h^{m}_{i,j,k}\right)\\
&+C_{i,j,k-\frac{1}{2}}\left(h^{m}_{i,j,k-1}-h^{m}_{i,j,k}\right)+C_{i,j,k}\left(h^{m}_{i,j+1,k}-h^{m}_{i,j,k+1}\right)\\
&+P_{i,j,k}h^{m}_{i,j,k}+Q_{i,j,k}=S^{s}_{i,j,k}\Delta x_{i,j,k}\Delta y_{i,j,k}\Delta z_{i,j,k}\frac{h^{m}_{i,j,k}-h^{m-1}_{i,j,k}}{\Delta t}
\end{aligned}$$

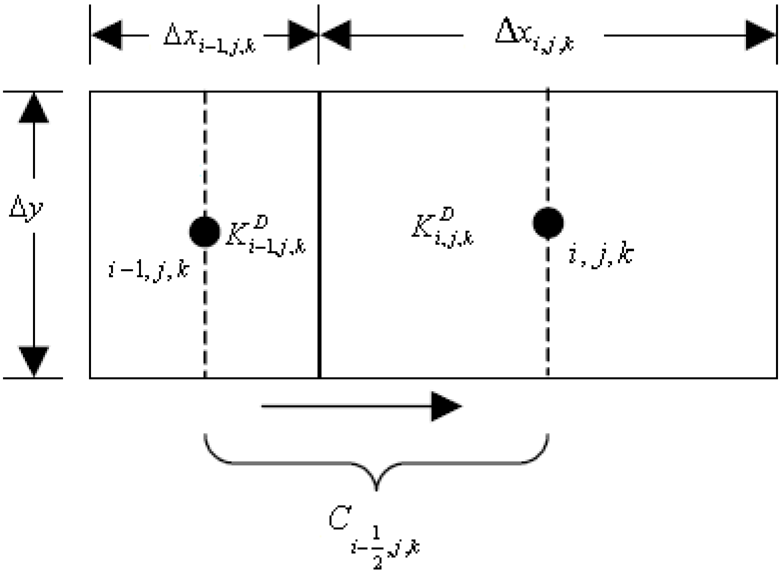
Equation 7

In this equation the hydraulic conductance needs to be specified in between cell centres; however the only known parameters are in the cell centre. To determine how the hydraulic conductance depends on parameters specified in the cell centre an upscaling rule has to be used, appendix III. This rule states that the hydraulic conductances of stacked layer perpendicular to the flow can be replaced by a conductance given by;

$$\frac{1}{C}=\sum_{i=1}^{n}\frac{1}{C_i}$$

Equation 8

Were C_i is the conductance for the individual stacked layers. There can be distinguished between two cases, the horizontal and vertical case. Firstly the horizontal case with again as an example the left face;



Figuur 19 Vertical hydraulic conductance

If the upscaling rule is applied the following is found;

$$\frac{1}{C_{i-\frac{1}{2},j,k}}=\frac{\frac{1}{2}\Delta x_{i-1,j,k}}{K^{D}_{i-1,j,k}\Delta y}+\frac{\frac{1}{2}\Delta x_{i,j,k}}{K^{D}_{i,j,k}\Delta y}$$

Equation 9

As mentioned in the introduction, in MIPWA Δx and Δy are chosen constant and equal. This makes;

$$\frac{1}{C_{i-\frac{1}{2},j,k}} = \frac{1}{2K^D_{i-1,j,k}} + \frac{1}{2K^D_{i,j,k}} = \frac{1}{2}\frac{K^D_{i-1,j,k} + K^D_{i,j,k}}{K^D_{i-1,j,k}K^D_{i,j,k}}$$

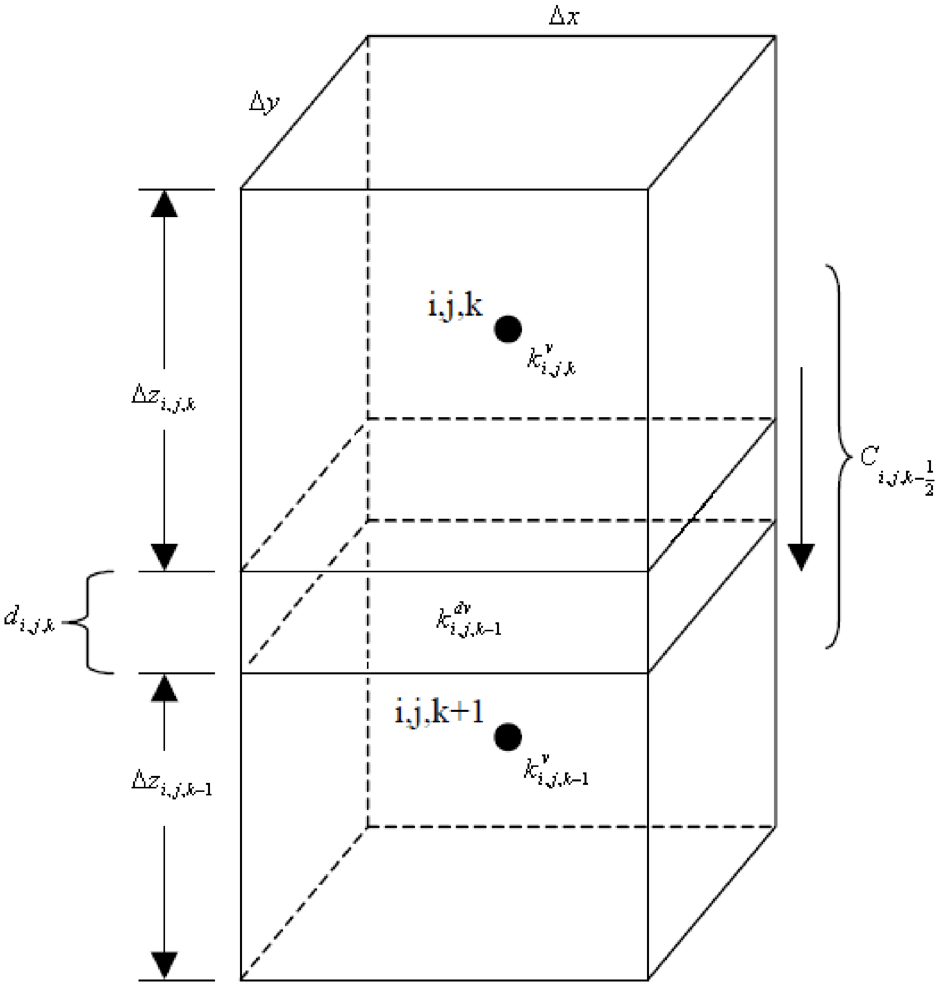
Equation 10

and thus;

$$C_{i-\frac{1}{2},j,k} = \frac{2K^D_{i-1,j,k}K^D_{i,j,k}}{K^D_{i-1,j,k} + K^D_{i,j,k}}$$

Equation 11

Similar expressions can be found for the other 3 faces. Now the horizontal case with as an example the lower face;



Figuur 20 Horizontal hydraulic conductance

As mentioned, it can be seen that an extra “virtual” layer is added to compensate for decrease in vertical conductance. If the upscaling rule is applied the following is found;

$$\frac{1}{C_{i,j,k-\frac{1}{2}}}=\frac{1}{\dfrac{k^{v}_{i,j,k-1}\Delta x\Delta y}{\frac{1}{2}\Delta z_{i,j,k-1}}}+\frac{1}{\dfrac{k^{dv}_{i,j,k}\Delta x\Delta y}{d_{i,j,k}}}+\frac{1}{\dfrac{k^{v}_{i,j,k}\Delta x\Delta y}{\frac{1}{2}\Delta z_{i,j,k}}}$$

Equation 12

Were $k^{dv}_{i,j,k}$ is the vertical hydraulic conductivity of the confining layer in $\left[LT^{-1}\right]$ and $d_{i,j,k}$ is the thickness of the confining layer. In MIPWA it was chosen that the hydraulic conductance is fully determined by the conductance of the confining layer. In other words $k^{dv}_{i,j,k} << k^{v}_{i,j,k-1}, k^{v}_{i,j,k}$, which means that;

$$\frac{1}{C_{i,j,k-\frac{1}{2}}}\approx\frac{1}{\dfrac{\Delta x\Delta y}{c_{i,j,k}}}\Rightarrow C_{i,j,k-\frac{1}{2}}=\frac{c_{i,j,k}}{\Delta x\Delta y}$$

Equation 13

Were $c_{i,j,k}$ is the resistance of the confining layer in $\left[T\right]$ and is given by $c_{i,j,k}=\dfrac{d_{i,j,k}}{k^{dv}_{i,j,k}}$. A similar expression can be found for the upper face. If all these expressions are filled in the original equation the following is found;

$$\begin{aligned}&\frac{K^{D}_{i,j,k}K^{D}_{i,j-1,k}}{K^{D}_{i,j,k}+K^{D}_{i,j-1,k}}\left(h^{m}_{i,j-1,k}-h^{m}_{i,j,k}\right)+\frac{K^{D}_{i,j,k}K^{D}_{i,j+1,k}}{K^{D}_{i,j,k}+K^{D}_{i,j+1,k}}\left(h^{m}_{i,j+1,k}-h^{m}_{i,j,k}\right)\\&+\frac{K^{D}_{i-1,j,k}K^{D}_{i,j,k}}{K^{D}_{i,j,k}+K^{D}_{i-1,j,k}}\left(h^{m}_{i-1,j,k}-h^{m}_{i,j,k}\right)+\frac{K^{D}_{i,j,k}K^{D}_{i+1,j,k}}{K^{D}_{i,j,k}+K^{D}_{i+1,j,k}}\left(h^{m}_{i+1,j,k}-h^{m}_{i,j,k}\right)\\&+\frac{\Delta x\Delta y}{c_{i,j,k}}\left(h^{m}_{i,j,k-1}-h^{m}_{i,j,k}\right)+\frac{\Delta x\Delta y}{c_{i,j,k+1}}\left(h^{m}_{i,j+1,k}-h^{m}_{i,j,k+1}\right)\\&+P_{i,j,k}h^{m}_{i,j,k}+Q_{i,j,k}=S_{i,j,k}\Delta x\Delta y\frac{h^{m}_{i,j,k}-h^{m-1}_{i,j,k}}{t^{m}-t^{m-1}}\end{aligned}$$

Equation 14

Usually this is rewritten such that all the constants are on the rigth and all the variables are on the left, this makes;

$$A^{m}_{i,j,k}h^{m}_{i,j,k}+B_{i,j,k}h^{m}_{i-1,j,k}+C_{i,j,k}h^{m}_{i+1,j,k}+D_{i,j,k}h^{m}_{i,j-1,k}+E_{i,j,k}h^{m}_{i,j+1,k}+F_{i,j,k}h^{m}_{i,j,k-1}+G_{i,j,k}h^{m}_{i,j,k+1}=X^{m}_{i,j,k}$$

Equation 15

Were $A^{m}_{i,j,k}, B_{i,j,k}, C_{i,j,k}, D_{i,j,k}, E_{i,j,k}, F_{i,j,k}, G_{i,j,k}, X^{m}_{i,j,k}$ are constant and depended on the following parameters;
$K^{D}_{i,j,k}, K^{D}_{i-1,j,k}, K^{D}_{i+1,j,k}, K^{D}_{i,j-1,k}, K^{D}_{i,j+1,k}, c_{i,j,k}, c_{i,j,k+1}, \Delta x, \Delta y, \Delta t, S_{i,j,k}, P_{i,j,k}, Q_{i,j,k}, h^{m-1}_{i,j,k}$
These are specified for each cell and for each time step. What is left is an equation with 7 unknowns. Next the initial and boundary conditions needs to be specified.

3.4 Initial and Boundary conditions

As mentioned to solve the problem an initial and for each face a boundary condition has to be specified. In the upcoming Sections these will be discusses.

3.4.1 Initial condition

In order to calculate the head, the head in the cell one time step before, needs to be specified. In order to start the calculation the, needs to be specified in each cell, since there is no time step before the start, this is called the initial condition. The MIPWA model in this research will run from 2001 to 2010. The MIPWA consortium calibrated the model parameters with a stationary run, more on this in the next Section. The results of this stationary run are used for the initial conditions of the original dynamic runs fot the period 1989-2001. Since the stationary run represent the average conditions from 1989 to 2001, there is some error in the initial conditions when used for this case, especially because several hydrological changes have taken place in the Elperstroom since then. To be sure these will not affect the outcome the model the First two years of the model run will not be considered by the analysis of the results.

3.4.2 Boundary conditions

In the boundary condition we can distinguish between two kinds, the First is the Dirichlet boundary condition. This condition specifies the head on the boundary, in the MIPWA model this boundary condition is imposed on the right, left, front and back boundary. An example is given for the left boundary;

$$A^m_{1,j,k} h^m_{1,j,k} + B_{1,j,k} h^{lb}_{j,k} + C_{1,j,k} h^m_{2,j,k} + D_{1,j,k} h^m_{1,j-1,k} + E_{1,j,k} h^m_{1,j+1,k} + F_{1,j,k} h^m_{1,j,k-1} + G_{1,j,k} h^m_{1,j,k+1} = X^m_{1,j,k}$$

Equation 16

Were $h^{lb}_{j,k}$ is the head on the left boundary in row j and layer k . This results in an equation with 6 unknowns, one less then the original. The second type boundary condition is the Neumann conditions. This boundary conditions specifies the flux through the boundary, this boundary conditions is used for the upper and lower boundary condition. Firstly the lower boundary, since this is the geohydrological base, it is impermeable for groundwater and thus no flux will come through, if we apply this to Darcy's law;

$$Q^m_{i,j,7+\frac{1}{2}} = -k^h_{i,j,7+\frac{1}{2}} \Delta x \Delta y_{i,j,7+\frac{1}{2}} \frac{h^m_{i,j,7} - h^m_{i,j,8}}{x_{i,j,7} - x_{i,j,8}} = 0$$

Equation 17

Following from this;

$$h^m_{i,j,7} = h^m_{i,j,8}$$

Equation 18

And filling it in the original equation gives;

$$\left(A^m_{i,j,7} + F_{i,j,7}\right) h^m_{i,j,7} + B_{i,j,7} h^m_{i-1,j,7} + C_{i,j,7} h^m_{i+1,j,7} + D_{i,j,7} h^m_{i,j-1,7} + E_{i,j,7} h^m_{i,j+1,7} + G_{i,j,7} h^m_{i,j,6} = X^m_{i,j,7}$$

Equation 19

Giving an equation with one unknown less. For the upper boundary the flux is given by the groundwater recharge which is calculated by CAPSIM, this will be explained in the coming Section. If this is applied to Darcy's law.

$$Q^m_{i,j,1-\frac{1}{2}} = N\left(h^m_{i,j,1}\right) \Delta x \Delta y = -k^h_{i,j,1-\frac{1}{2}} \Delta x \Delta y \frac{h^m_{i,j,1-\frac{1}{2}} - h^m_{i,j,k}}{z_{i,j,1-\frac{1}{2}} - z_{i,j,k}} = -C_{i-\frac{1}{2},j,k} \left(h^m_{i-1,j,k} - h^m_{i,j,k}\right)$$

Equation 20

Were $N\left(h_{i,j,1}^{m}\right)$ is the groundwater recharge in $\left[LT^{-1}\right]$ which is a function of $h_{i,j,1}^{m}$. Giving;

$$\begin{aligned}
&\frac{K_{i,j,k}^{D}K_{i,j-1,k}^{D}}{K_{i,j,k}^{D}+K_{i,j-1,k}^{D}}\left(h_{i,j-1,k}^{m}-h_{i,j,k}^{m}\right)+\frac{K_{i,j,k}^{D}K_{i,j+1,k}^{D}}{K_{i,j,k}^{D}+K_{i,j+1,k}^{D}}\left(h_{i,j+1,k}^{m}-h_{i,j,k}^{m}\right)\\
&+\frac{K_{i-1,j,k}^{D}K_{i,j,k}^{D}}{K_{i,j,k}^{D}+K_{i-1,j,k}^{D}}\left(h_{i-1,j,k}^{m}-h_{i,j,k}^{m}\right)+\frac{K_{i,j,k}^{D}K_{i+1,j,k}^{D}}{K_{i,j,k}^{D}+K_{i+1,j,k}^{D}}\left(h_{i+1,j,k}^{m}-h_{i,j,k}^{m}\right)\\
&+N\left(h_{i,j,1}^{m}\right)\Delta x\Delta y+\frac{\Delta x\Delta y}{c_{i,j,k+1}}\left(h_{i,j,k}^{m}-h_{i,j,k+1}^{m}\right)\\
&+P_{i,j,k}h_{i,j,k}^{m}+Q_{i,j,k}=S_{i,j,k}\Delta x\Delta y\,\frac{h_{i,j,k}^{m}-h_{i,j,k}^{m-1}}{t^{m}-t^{m-1}}
\end{aligned}$$

Equation 21

Giving a slightly different equation with one unknown less;

$$A_{i,j,k}^{m*}h_{i,j,k}^{m}+B_{i,j,k}h_{i-1,j,k}^{m}+C_{i,j,k}h_{i+1,j,k}^{m}+D_{i,j,k}h_{i,j-1,k}^{m}+E_{i,j,k}h_{i,j+1,k}^{m}+G_{i,j,k}h_{i,j,k+1}^{m}=X_{i,j,k}^{m*}$$

Equation 22

3.4.3 Solving the system

A system of equation can only be solved if the problem is fully determined, meaning that there are as much unknown as equations. This is the case, since for each cell in the model area an equation is computed, giving $i\cdot j\cdot k$ equations. The equations, taking into account the boundary conditions, are all only depended on the head in the modelling domain. Meaning there are also $i\cdot j\cdot k$ unknowns, the problem is fully determined and can be solved. The details of the technique to solve this system with many unknown will not be discussed. It involves iteration, meaning that for each equation an initial guess in filled in $h_{i,j,k}^{*}, h_{i-1,j,k}^{*}, h_{i+1,j,k}^{*}, h_{i,j-1,k}^{*}, h_{i,j+1,k}^{*}, h_{i,j,k-1}^{*}, h_{i,j,k+1}^{*}$ most probably this guess is wrong resulting in an error term;

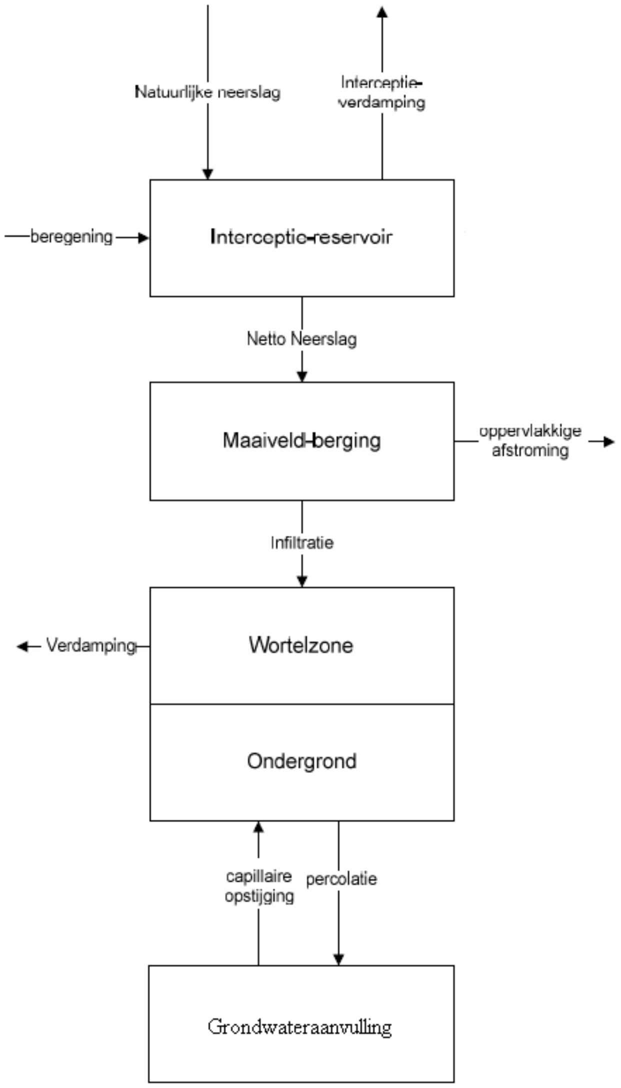
$$\Delta=A_{i,j,k}^{m}h_{i,j,k}^{*}+B_{i,j,k}h_{i-1,j,k}^{*}+C_{i,j,k}h_{i+1,j,k}^{*}+D_{i,j,k}h_{i,j-1,k}^{*}+E_{i,j,k}h_{i,j+1,k}^{*}+F_{i,j,k}h_{i,j,k-1}^{*}+G_{i,j,k}h_{i,j,k+1}^{*}-X_{i,j,k}^{m}$$

Equation 23

Based on this error the initial guess is updated which will decrease the error; this is repeated until a certain criterion is met.

3.5 Groundwater recharge

As mentioned the groundwater recharge is modelled with CAPSIM. The modelling concept of CAPSIM is that of coupled reservoirs. Here the different residences of the water are seen as different reservoirs and the processes that influence this residence are modelled as fluxes between the reservoirs. In CAPSIM this looks as follows;



Figuur 21 Processes modelled by CAPSIM

It all starts with rain, often this rain will not directly drop on the soil but will first be intercepted by vegetation or impermeable objects. This is called the interception reservoir. In times of drought agricultural grounds may be irrigated, this is seen as an extra precipitation. From the reservoir part of the water will evaporate back to the atmosphere. However the interception reservoir has a limited size and usually the total precipitation is so large that the reservoir quickly floods and the water will drop on the soil. This is the next reservoir. Due to the limited infiltration capacity of the soil not all water will infiltrate and puddles will form. Part of the water will infiltrate later and a part will runoff to the surface water. In MIPWA it was chosen to not explicitly model the surface water but to use a fixed water level. How this is done will be discussed in the next Section. Because of this the (sub)surface runoff will lead to a rise in surface water levels but will disappear out of the model. It chosen that the puddles can not be deeper then $2cm$ all the excess water will again disappear out of the model. The water that infiltrates it will end up in the next reservoir; the root and unsaturated zone. Here part of the water can be taken up by the roots and by evaporate by the vegetation. Part of the water will percolate to the saturated zone, the groundwater. In times of drought, the moisture demand may be so large in the root and unsaturated zone that due to capillary rise water may be transported back to the root zone. The difference between the capillary rise and the percolation is called the groundwater recharge.

The fluxes between the reservoir are in reality depended on a large number of parameters, in CAPSIM these are simplified to the following; precipitation, evaporation, land-use, percentage paved surface, percentage permanent surface water, soil physical unit, infiltration capacity and the root and unsaturated thickness. The precise mathematical expression describing these fluxes will not be discussed in the research, for this is referred to **(Van Walsum, 2006).**

- Time series available from KNMI stations were used to determine the precipitation.
- To determine the evaporation the method of Makkink was used. In this method the reference crop evaporation is used, that is the amount of water that evaporates from grassland under the assumption it has a good supply of water and nutrients. The reference crop evaporation is calculated based on the solar irradiance and is directly available form KNMI stations. From this the maximal potential evaporation is calculated. This is done by multiplying the Makkink evaporation by a crop factor. This factor is depend on the type of crop and is tabulated for a great number of crops **(Cultuurtechnisch Vademecum, 1988).** With the map of the land-use in the MIPWA database the crops factor is calculated for the whole MIPWA modelling area. This same map is used to determine the size of the interception reservoir, since this is depended of the type of land-use.
- In MIPWA it is assumed that paved area does not contribute to the groundwater recharge. The recharge via the surface water will not be calculated in CAPSIM but is included in de MODFLOW code. To compensate for this the percentage of paved area and surface water per cell should be known, this is derived from the land-use map.
- The infiltration capacity determines with which speed the precipitation infiltrates and thus determines the amount of surface runoff. This is derived from the saturated transmissivity of the first layer of the MODFLOW model.
- The soil physical unit determines the capillary rise and the size of the root and unsaturated zone. The soil physical unit is determined using soil maps of different areas in the Netherlands. **(Alterra, 2006)** The capillary rise and the size of the root and unsaturated zone are both depended of the head in the phreatic aquifer. To take this into account, the groundwater recharge is calculated dynamically each time step depending on the head in the phreatic aquifer. So each time step a $N\left(h_{i,j,1}^{m}\right)$ in $\left[LT^{-1}\right]$ is calculated each time step.

3.6 Sources and sinks

In this Section there will be discussed how all the sources and sinks are incoporated in the source/sink term in the equation

3.6.1 Groundwater extraction

At some locations in the model groundwater may be abstracted, for example for drinking water or by industries. All extraction more then $50.000\, m^3/yr$ are considered in the MIPWA model, since it is obligated to report extractions of this size and greater the provinces has a good archive of all extractions. This archive was used to determine where how much is abstracted. As earlier discussed the sources and sink terms are considered up to a constant linear dependent on the head in the cell, equation 3. The groundwater extraction is assumed constant for each time step and independent of the head, incorporating this in the equation yields;

$$W_{i,j,k} = P_{i,j,k}^{m} h_{i,j,k}^{m} + A_{i,j,k}^{m} + \ldots$$

Equation 24

Were $A_{i,j,k}^{m}$ is the volumetric flux of the extraction given in $\left[L^3T^{-1}\right]$.

3.6.2 Irrigation

It is also possible to model irrigation. For each surface grid cell there is determined whether it can irrigate. In MIPWA it is assumed that irrigation can only occur within a certain period, these can be seen in the following table;

Tabel 1 Start and end of the irrigation period

Landuse	**Start**	**End**
Grassland	15 May	1 October
Potatoes	1 July	1 September
Sugar beets	1 July	1 September
Other	1 May	1 September

If during the irrigation period CAPSIM calculates a soil suction of more then 0.33 bar there will be irrigated. The irrigation rate is $1.8\,mm/day$ including an irrigation loss of 10%. The irrigation is added to the effective precipitation as discussed. The groundwater is assumed to be extracted form the groundwater giving;

$$W_{i,j,k} = P^m_{i,j,k} h^m_{i,j,k} + A^m_{i,j,k} + I^m_{i,j,k} + \ldots$$

Equation 25

Were $I^m_{i,j,k}$ is the volumetric flux of the irrigation given in $\left[L^3T^{-1}\right]$

3.6.3 Surface water

The interaction between surface water is a Darcy's law like equation is assumed;

$$q^{\;\;m}_{river\,i,j,k} = SA_{i,j,k} \frac{h^{\;\;m}_{river\,i,j,k} - h^m_{i,j,k}}{R_{i,j,k}} = C^{riv}_{i,j,k}\left(h^{\;\;m}_{river\,i,j,k} - h^m_{i,j,k}\right)$$

Equation 26

With $q^{\;\;m}_{river\,i,j,k}$ is the recharge/drainage from the cell from/to the surface water $SA_{i,j,k}$ is the total area surface water of the cell in $\left[L^2\right]$, $R_{i,j,k}$ the resistance of the surface water in $\left[T\right]$, simplifying this yields $C^{riv}_{i,j,k}$ in $\left[L^2T^{-1}\right]$ and $h^{\;\;m}_{river\,i,j,k}$ the water level in $\left[L\right]$. This can be rewritten in the following form;

$$q^{\;\;m}_{river\,i,j,k} = -C^{riv}_{i,j,k} h^m_{i,j,k} + C^{riv}_{i,j,k}\, h^{\;\;m}_{river\,i,j,k}$$

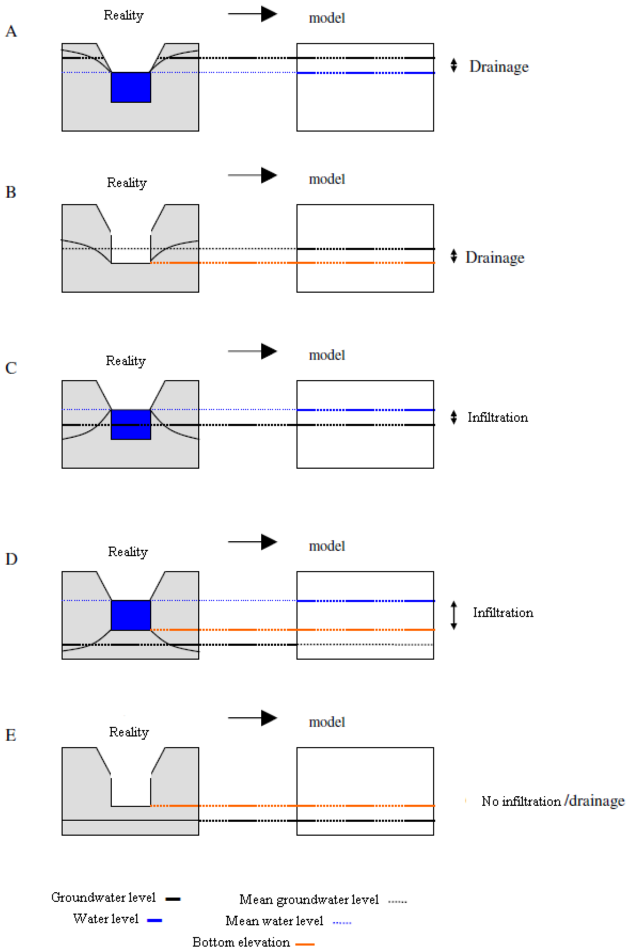
Equation 27

This is in the same form as the source/sink term. Filling this in gives;

$$W_{i,j,k} = \left(-C^{riv}_{i,j,k}\right) h^m_{i,j,k} + \left(A^m_{i,j,k} + C^{riv}_{i,j,k}\, h^{\;\;m}_{river\,i,j,k} + I^m_{i,j,k}\right) + \ldots$$

Equation 28

Using a detailed map of the modelling area, the $SA_{i,j,k}$ could be determined and with the formula of Ernst the resistance was determined, more on this in a later Section. The water levels in the surface water are maintained by the Dutch water boards and are archived. From this archive the water levels were determined. However some care should be taken how to choose the water levels, this is illustrated in the Figure 22;



Figuur 22 Different surface water scenarios

In the case of A and C it is straight forward, the water level is just the water level maintained by the water boards. However in case B and E a dry waterway is considered, usually the case in agricultural lands were small ditches drain all the rainwater from the lands to larger waterways. These ditches do not have a permanent water level and can only drain groundwater. In such a case instead of using the water level the bottom elevation is used to calculate drainage. Since these ditches can not infiltrate water this is set to zero. The last special case is D, when the groundwater levels are so low that they are beneath bottom elevation. In that case not the head in the cell is used but the bottom elevation.

3.6.4 Drainage

The last process is drainage, a similar equation as that for surface water is used;

$$q_{i,j,k}^{drain} = C_{i,j,k}^{drain}\left(d_{i,j,k}^{drain} - h_{i,j,k}^{m}\right)$$

Equation 29

With $C_{i,j,k}^{drain}$ the conductance of the drain in $\left[L^2T^{-1}\right]$and $d_{i,j,k}^{drain}$ the drain depth in $\left[L\right]$. Reareging terms gives;

$$q_{i,j,k}^{drain} = \left(-C_{i,j,k}^{drain}\right)h_{i,j,k}^{m} + \left(C_{i,j,k}^{drain}d_{i,j,k}^{drain}\right)$$

Equation 30

Since the drain can only drain and not infiltrate water, whenever $q_{i,j,k}^{drain}$ is positive it is set to zero.

Putting it all together this results in the following source/sink term;

$$W_{i,j,k} = -\left(C^{riv}_{i,j,k} + C^{drain}_{i,j,k}\right)h^{m}_{i,j,k} + \left(A^{m}_{i,j,k} + C^{riv}_{i,j,k}\,\underset{river\,i,j,k}{h}{}^{m} + C^{drain}_{i,j,k}\,d^{drain}_{i,j,k} + I^{m}_{i,j,k} \right)$$

Equation 31

4 Analysis current MIPWA situation

4.1 Modelling area

MIPWA is a model of the entire northern part of the nerterlands. In order to calculate th effects of the scenarios in the Elperstroom a “crop” of this model is to be used. To accurately model the different scenarios the modelling area should be sufficiently large in order to have no effect of the boundary conditions on the model results. The modelling area should however not be unnecessarily large, to prevent long computing time. To determine the right size the following equation is used;

$$\lambda = \sqrt{Kd \cdot c}$$

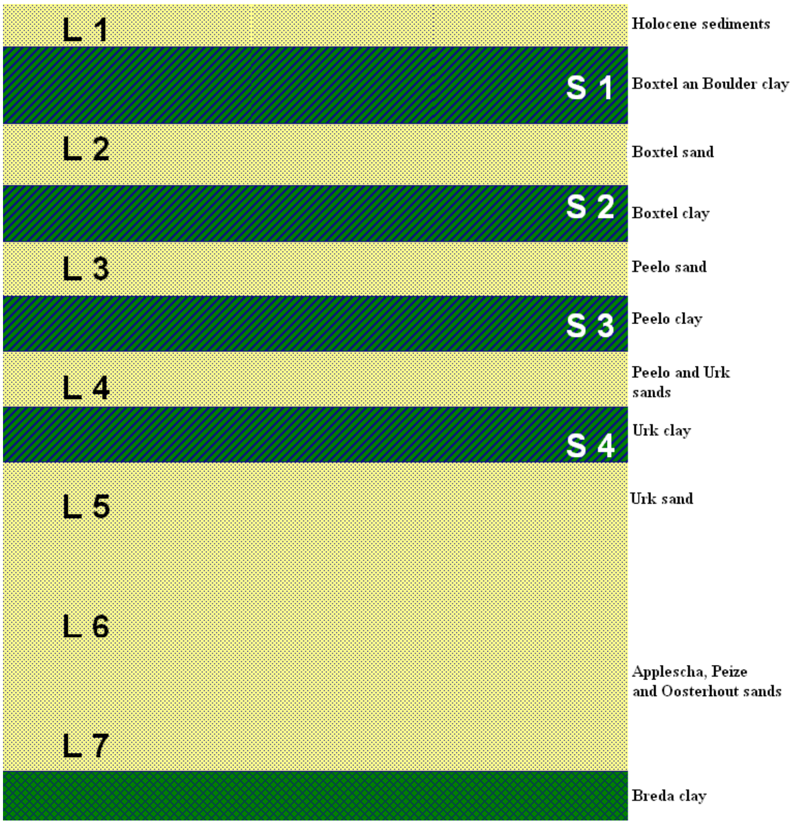
Equation 32

Where λ is the radius of influence of a certain effect in [m] . To be sure, the largest Kd and largest c were used, 6000 m2/day and 6000 days respectively. This gives a radius of 6 km. For the ease of modelling an rectangular model area was chosen of $12 \times 12 km$ with in approximately the middle the natura 2000 area the Elperstroom, Figure I1.

4.2 Model parameters

As was seen before for each cell, $K_{i,j,k}^{D}$ and $c_{i,j,k}$ were specified in MIPWA these were determined based on REGIS-II (REgionaal Geohydrologisch InformatieSysteem). Based on the thickness and hydraulic properties $K_{i,j,k}^{D}$ and $c_{i,j,k}$ were determined.

The schematization of the modelling area of the Elperstroom is shown in Figure 23.



Figuur 23 Schematization of the geological formations in MIPWA

How this is translated to a $K^{D}_{i,j,k}$ and $c_{i,j,k}$ can be seen in, Figure V 1 to V 11.

The parameters for the surface water that are required are; conductance, water level, bottom level, ratio between the conductance when infiltrating and draining. These parameters are based on information given by the provinces, water boards and ministry of transport, Public works and water management (Rijkswaterstaat), GIS-analysis and calibration of the model-parameters.

The water level guaranty is used to determine whether a waterway can run dry during the summer or whether there is always a minimum level guaranteed by inlet of water. In waterway where there is no water level guaranty the bottom level is set equal to the water level, so no infiltration can occur in the summer, see Figure 21. In all other cases the bottom levels are set equal to the bottom levels provided. To determine to which model layers the surface water cuts, the bottom height is then compared to the levels of the formations in REGIG II.1.

For the modelling of the effect of drainage, the drain depth and the drain resistance should be known. The problem was that there is no archive of installed drainage. In an earlier study for the STONE-model (Samen Te Onderzoeken Nutriënten Emissiemodel) an analysis was done of some small area where there was an archive. From this data a statistical analysis was made from which the presence of drainage could be derived based on land-use, soil-type and groundwater regime. For some areas extra information was provided from the archive of five large drainage construction companies. This information was also used to calculate the drainage resistance.

4.3 MIPWA calibration

When determining the model parameters there will always be uncertainty in the results. For instant all the subsurface parameters are based on interpolations of few boreholes, the crop factor is based on statistical analysis. Inherent to these techniques is that there always will be uncertainty. So there will always be a difference between what you model and what you measure, this is called the residue. To further improve the model the MIPWA consortium did a calibration, here model results were compared with actual measurement from the field. Parameters were then adjusted so that the residue would decrease. The measurements in the field consist of 8171 time series measured in different locations in the model in different layers. Based on this the model was Firstly calibrated stationary, only the subsurface parameters were adjusted. Due to computing time there was chosen to calibrate with a cell size of $1000\times1000m$ adjustments were then downscaled to $25\times25m$. Next a dynamic calibration was done, the surface water resistances, the size of the root zone reservoir were adjusted. Again this was first done for a $1000\times1000m$ grid and the downscaled to $25\times25m$.

5 Actualisation MIPWA

As discussed in the last Section, inherent to determining model parameters is uncertainty. For this Thesis an effort was made to further improve the model parameters. This was done making use of local knowledge and a large number of measurements. Two sets of parameters were adjusted which will be discussed in the coming Sections, Firstly the lithografic parameters and next the surface water parameters. The parameters were then further calibrated based on more local monitoring wells compared to the original MIPWA calibration.

5.1 Subsurface parameters

As discussed in the second Chapter, the appointed habitat types require an alkaline buffered upwards seepage. Large part of the upwards seepage is controlled by the resistance of the underlying aquitards, an effort was made to more precisely determine these parameters. Three aquitards can be distinguished in the study area, the boulder clay from the Drenthe formation, the fine river sediments from the Boxtel formation and the co called pot-clay in the Peelo formation. In MIPWA the boulder clay is schematized in the virtual layer S1 together with holocen sediments and peat river clay, the Boxtel clay in S2 and the Peelo clay in S4.

The improvement is done by an analysis of boreholes. The boreholes used are shown in appendix I, Figure I 2. It can be seen that most of the boreholes are less then 3.5 m meter deep, however especially in and around the Elperstroom area there are also more middle deep and deep boreholes. The Boreholes are downloaded from the DINO-database (Data en Informatie van de Nederlandse Ondergrond), this is a central storage point with data about the deep and middle deep subsurface.

5.1.1 Peelo clay

The REGIS II.1 interpolations show a large tongue shaped Peelo clay formation, Figure I 3. The blue dots are the boreholes were according to REGIS clay is found. However in the borehole logs there is no description of clay. For example borehole B17E0084; according to REGIS there is a clay layer from $-1.8;-13.9 mN.A.P.$. However the borehole log, Figure I 4, shows two layers, one grey-brown very fine sand layer and a grey very fine sand layer. The automated classification used in REGIS classifies this as a clay layer. It should also be noted that the clay layer is not fully penetrated by the borehole so it is uncertain what the actual thickness of the layer is. Strangely if we look at borehole B17E0083, Figure I 5, we find again a layer of very fine grey sand, $-8;-13.9 mN.A.P.$. However this layer is not classified as a clay layer despite it having a even lower mean particle size of $100\mu m.$ compared to $120\mu m.$ and $140\mu m.$ for the layers classified as clay. The same holds for the other boreholes, there is only evidence of very fine grey sand layers according to the logs. It is however known that sand in the Peelo formation is usually very fine and has a grey colour **(Ebbing, 2003)**. Probably the classification of REGIS wrongly classifies the sand as clay. In this Thesis it is thus assumed that there is no Peelo clay in the modelling area. However in the quasi 3D approach in MIPWA, it is assumed that there is a vertical resistance of zero, equation 11,12, and flow will only be horizontal. However due to very fine sand in the Peelo formation the vertical resistance can not be neglected. To compensate for this resistance in S3 is set to $150 days$ this is based on a vertical hydraulic conductivity of $0.2 m/day$ and a thickness of $30m.$ **(Gieske, 1988)**

5.1.2 Boxtel clay and Drenthe boulder clay

Next the Boxtel clay and boulder clay were investigated, in REGIS the Boxtel clay is divided in two separate layers, Figure I 6 and I 7. The boulder clay is shown in Figure I 8. In general the Boxtel will be above the boulder clay. If we look at the individual boreholes were the REGIS interpolations are based on, it can be seen that in almost al the cases when there is boxtel clay there is no boulder clay and visa versa. If the genesis of the different formations is taken in consideration this is also what one expects. Chronologically the boxtel clay is formed after the boulder clay as river sediment, most probable flushed boulder clay. The river from which the boxtel clay originated is known to cut trough the boulder clay. This can clearly be seen in Figure I 8, river shaped area can be recognized where there is no boulder clay.

In the few rare cases that both the Boxtel and boulder clay are found, they both are in direct contact or have a small layer of sand in between and can be seen as one single layer. For example, B17E0035, here the boxtel clay is from $17.3;17.0mNAP$ and the boulder clay from $17.0;14.8mNAP$. From now it will be assumed that the boxtel clay and bloulder clay can be seen as one single clay layer, the first aquitard (S1). For which one resistance will be calculated.

Firstly a map of the thickness of the total clay layer was made. This was based on all the DINO boreholes available in the modelling area. A python script was made which read all the borehole logs and extracted the clay layer thickness. The boxtel clay is known to exist out of many small clay layers with small layer of sand in between. These different layers are formed during different flooding events. This was solved by adding the individual thicknesses together. From this a point map was made, Figure I 2. All the boreholes were the layer was not fully penetrated were neglected. From this an interpolation was made using an inverse distance weighted scheme;

$$t(x,y) = \sum_{i=1}^{n} \frac{w_i(x,y)T_i}{\sum_{i=1}^{n} w_i(x,y)} ; w_i(x,y) = \left(\frac{1}{\sqrt{(x-x_i)^2 + (y-y_i)^2}} \right)^p$$

Equation 33

Were $t(x,y)$ is the interpolated tickness at location $[x,y]$ both in $[m]$. And $T_1, T_2, \ldots, T_i, \ldots, T_n$ are the thicknesses in $[m]$ known at locations $[x_1,y_1],[x_2,y_2],\ldots,[x_i,y_i],\ldots,[x_n,y_n]$ in $[m]$ and p is the power parameter which is dimensionless. The power parameter was chosen equal to two. The result of this can be seen in Figure I 9. In a research **(Bakker, 1984)** measured the resistance of the boulder clay with different thicknesses in a similar location in Drenthe;

Table 2 Results research Bakker

Thickness [m]	Resistance [days]
0.5	20
1	100
2	400
4	1200
6	2000

From this a second order polynomial function was computed;

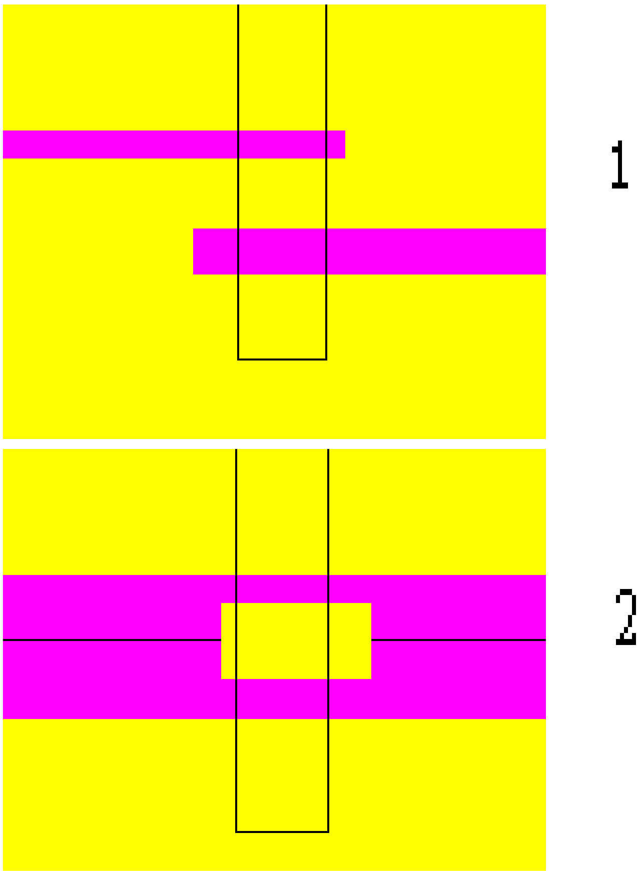
$$c(t) = 31.82t^2 + 148.65t$$

Equation 34

This was then applied to the entire thickness map with the following result, Figure I 9. It can be seen that especially to the north-west of the study area there is an area with a high resistance, here thicknesses up to $2m$ are measured. In the study area itself the thickness is less in the order of $0.2m$ and more to the east the clay layer is not found anymore.

5.1.3 Discussion

In most cases this assumption of one single clay layer will hold, because both layers are in direct contact or only one layer is present at the location. However in some boreholes there was a small sand layer in between the clay layers. In for example B17E0017, here the boxtel clay is $2.5;3.0mNAP$ and the boulder clay from $4.2;5.2.mNAP$. This can be interpret in two ways;



Figuur 24 Interpertation boreholes

The black lines indicate the bore core; both bore holes give the same core but imply different situations. In situation 2 the sand layer is enclosed by the two clay layers. Since when interpreting the boreholes the thicknesses of the individual layer were added a reasonable resistance will be calculated between the freatic aquifer and the first confined aquifer. Only vertical resistance of the sand layer is neglected, this is reasonable since the vertical resistance of the clay layers is much order higher. However in the first case the sand layer is not enclosed and will form a short circuit between the two aquifers were groundwater can exchange with almost no resistance. The interpolation however, “sees” this as one single layer with no interruption. The resistance in this case is overestimated. The same will happen if the multiple layers in the boxtel formation are added together.

The assumption that the resistance can be predicted by equation 33 will also cause some error. Firstly, Bakker already argued that there is a high variability in the resistance in boulder clay due to the unsorted nature of the boulder clay, which locally can contain gravel and boulders. In his research Bakker also mentioned a pumping test in another area, “Het Fochtelöerveen”. In this area also a pumping test was done to determine the resistance of the boulder clay, here a resistance of 2000 days was found for a thickness of 1.5m. Whereas if equation 33 is used a resistance of approximately 300 days is found. Bakker argues that this extra resistance is due to a gliede layer. Gliede is formed when smallest humus particles is peat wash down with the infiltrating water to a clay or sand layer. Here the particles clog the pores in the sand and clay, forming a peat layer with low permeability. Since in the Elperstroom a lot of peat is present in the subsurface it can be expected that Gliede layers are also present in the Elperstroom. Again this will cause an underestimation of the resistance. Secondly, an error can be expected due to the fact that based on resistance measurements of boulder clay the resistance of boxtel clay is calculated.

5.2 Surface water

Another important factor which influences the upwards seepage is the interaction between surface water and ground water. Through drainage and infiltration the waterways influence the water levels in the phreatic aquifer and even in the first confined aquifer. Since for the upwards seepage is, important some extra effort was put in determining the surface water parameters more accurate. The current parameters provided by MIPWA were found outdated many water management adjustments have been made over the past 10 years; so some improvement could be achieved in determining the conductance of the waterway, the water level and whether the bottom of a waterway penetrates through the clay layer. This was partly done by a field study and partly be analysing available data. The local water board, “Reest and wieden”, provided data the current water levels and bottom depths of major waterways. The region is depicted in Figure II 1. Because of the large area, the study was divided in two areas.

- In the Elperstroom a field study of the waterways and directly connected waterways, was done on the conductance of the waterways, water levels were updated and the penetration of the clay layer was checked. Also the thickness of the clay layer under the waterways are adjusted.
- For the remaining area only the water levels and clay layer penetration was validated, the conductance was used from the MIPWA database.

5.2.1 Field study conductance

The field study consisted of a classification of the waterways in three classes;

Class	Resistance	Description
1	$20 days$	Small trenches, ditches, shallow.
2	$5 days$	Moderate waterway. control groundwater levels in agricultural area
3	$1 day$	Large waterways levels controlled by weirs

The resistances are based on expert judgement of local experts and on values used in MPWA for similar areas. Firstly a map was made based on data available from the TOP10 ***(Kadaster, 2009)*** and the data provided by the water board. Also input was given from conversations with local terrain managers who had knowledge of the latest adjustments. With this map the different waterways were identified in the field and classified. The results are shown in Figure II 2. It can be seen that the lower part of the Elperstroom is mainly dominated by waterways of class 1,

Figuur 25 Surface water class 1 in the Reitma

The direct surrounding agricultural areas are dominated by class 2.

Figuur 26 Surface water class 2 in an agricultural land

There area two large waterways, class 3, which run on both lower flanks of the area.

Figuur 27 Waterway of class 3 on the flank of the Elperstroom

Next the area was divided into grids of $25 \times 25m$, in accordance to the MIPWA grid. For each grid cell the area of surface water per grid cell was calculated, this was done for each class. In Figure II 3, the total area of surface water per grid cell can be seen. Using the following upscaling rule, appendix III;

$$C^{riv}_{i,j,k} = C^{1}_{i,j,k} + C^{2}_{i,j,k} + C^{3}_{i,j,k} = \frac{SA^{1}_{i,j,k}}{R^{1}_{i,j,k}} + \frac{SA^{2}_{i,j,k}}{R^{2}_{i,j,k}} + \frac{SA^{3}_{i,j,k}}{R^{3}_{i,j,k}}$$

Equation 35

Were $SA^{1}_{i,j,k}, SA^{2}_{i,j,k}, SA^{3}_{i,j,k}$ are the areas of surface water per class and $R^{1}_{i,j,k}, R^{2}_{i,j,k}, R^{3}_{i,j,k}$ are the resistances of the different classes. The conductance can be calculated, resulting in Figure II 4. It can be seen that the two waterways on the flanks have and to the south of the Elperstroom have high conductance and will thus have a strong interaction with the groundwater. The waterways in the Elperstroom have lower conductance and thus less interaction with the groundwater, however the ditches and trances are more intensely and almost the whole area is covered.

5.2.2 GIS analysis of available data

The local water board provided a so called "legger", this is a database with all the major waterway of the area. In the legger areas are defined were all the waterway have the same water level, this water level is maintained by the water board. There is a lower water level and an upper water level. The upper water level is the level at which the weirs are set, meaning that the water will normally not excess this level, water will simply flow over the weir, usually during winter. If the water level is beneath the lower water level, the water board lets in water from outside the area to maintain water levels. This means that the water level will normally not be below the lower level, this is usually during the summer. These levels are used to determine $h^{m}_{river\,i,j,k}$ in equation 24. It was chosen to make it equal to the upper water level from October 1st to April 1st, from April 1st till October 1st the next year the levels are set equal to the lower water level.

In consultation with the local terrain managers, there is decided that all the waterways in the red arched area are removed from the model and rainwater will infiltrate to the subsurface. This was done because all the waterways in that area are not connected to any mayor waterways which transport the water out or in the area. This means that all the water that is collected in the waterways will infiltrate to the groundwater or evaporate. There is assumed that there is no difference between rainwater infiltrating or rainwater first collecting and then infiltrating.

Next was determined in which model layer the bottom of the waterways were, in other words does the waterway penetrates the clay layer. It was determined that all the waterways of class 1 and 2 do not penetrate the clay. The mean depth of these waterways was less then the mean thickness of the clay layer, so penetration can not be possible. For the waterways in class 3 the legger provides information about the bottom depth of the waterway. Making use of the interpolated clay layer there was determined whether the bottom of the waterway was above beneath or in the clay layer the results are in Figure II 7. If the waterway does penetrate the clay layers the conductance and water level were also set in layer 2, with half of the total conductance in layer 1 and half in layer 2. In other words it is assumed that the interaction between groundwater and surface water is evenly divided between the two aquifers. When the bottom of the waterway is in the clay layer, the amount by which it penetrates is subtracted from the clay thickness. This to assure a realistic calculation of the resistance of the clay under the waterway and thus a realistic interaction between the waterways and layer 2 trough the clay layer.

5.2.3 Discussion

The assumption that the water levels are always on the lower or upper bound is probably unrealistic, especially the sharp transitions between level at the 1st of April and October. It is more probable that the water levels will vary between the lower and upper bound, with in the summer the low levels and during the winter higher levels. Another uncertainty is the classification in the field study. Again it is unlikely that all the waterways exactly meet the characteristics of the class. For example the assumption that all the waterways in class 1 and 2 do not penetrate the clay layer is probably unrealistic. Since this is based on means of the thickness of the clay layer and depth, most probably there will be a small number of waterways that do penetrate, especially in class 2. The penetration of the waterways in class 3 is also some what uncertain. The measurements of the water board are at one single location per waterway. This single measurement is however used to determine whether the whole waterway penetrates the clay layer. There can be concluded that some care should be taken when analysing the results especially with respect to interaction with surface water.

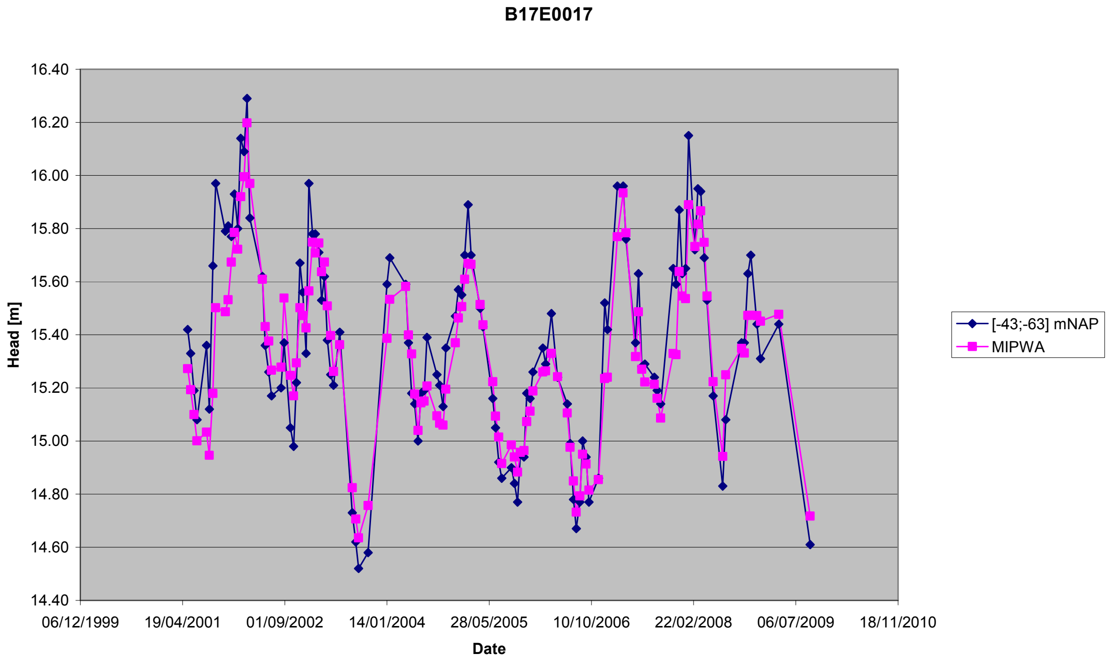
5.3 Calibration

5.3.1 Monitoring wells

The monitoring wells used in the calibration were divided in to three layers. The first layer is the one in under the Peelo sand, just beneath the aquitard representing the high vertical conductivity of this layer (L4). In this layer 4 wells were found that could be used. The next layer is the layer just beneath the boulder clay layer (L2), here 40 wells were found. And last the layer above the boulder clay, here 25 were selected. The time series from these monitoring wells were then compared to the results of the model. After several runs it was found that the best results are found when the surface water conductance is divided by two and the same holds for the resistance of the Peelo aquitard. A summary of the validation results is shown in Figure III 1, III 2 and III 3 from respectively the Peelo layer, beneath and above the clay. These maps show difference between the mean head of the model and monitoring wells.

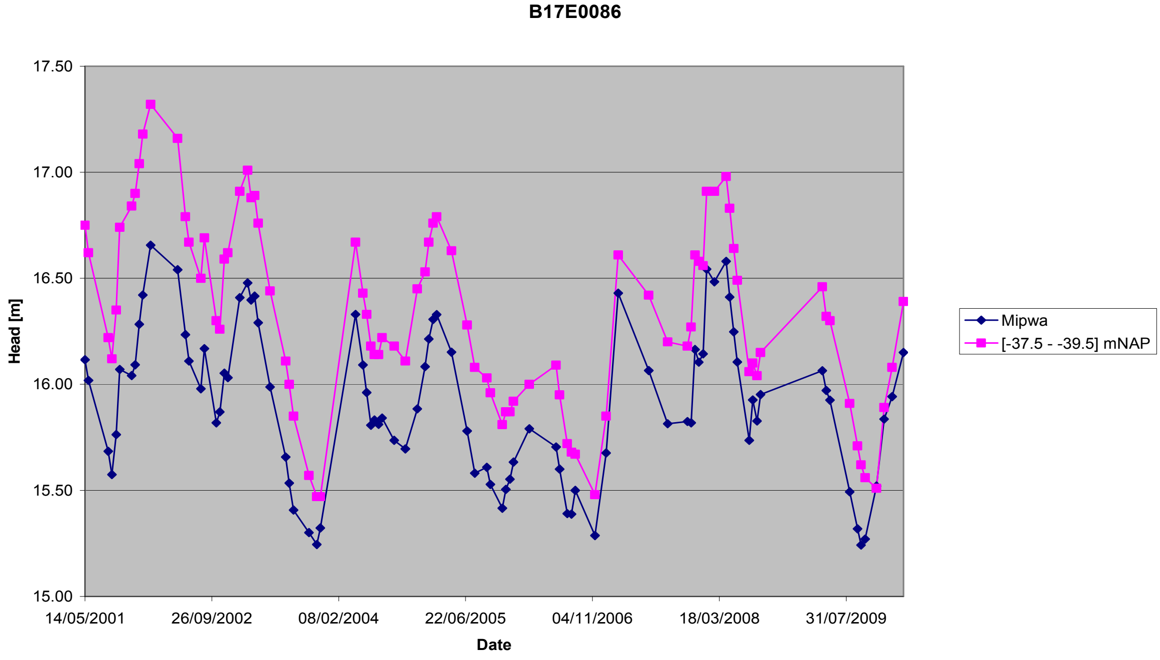
Deep groundwater

In the layer below the Peelo clay it can be seen that three of the four wells area reasonably close predicted in modelling standards, within a difference of $\pm 0.15m$. For example the B17E0017;



Figuur 28 Comparison between model and B17E0017

It can be seen that model nicely predicts the head, only some of the larger peaks are under estimated by the model. However the monitoring well in north-east shows al larger error of $-0.38m$. If we look at the time series it can be seen that this difference is almost structural over the whole modelling span;

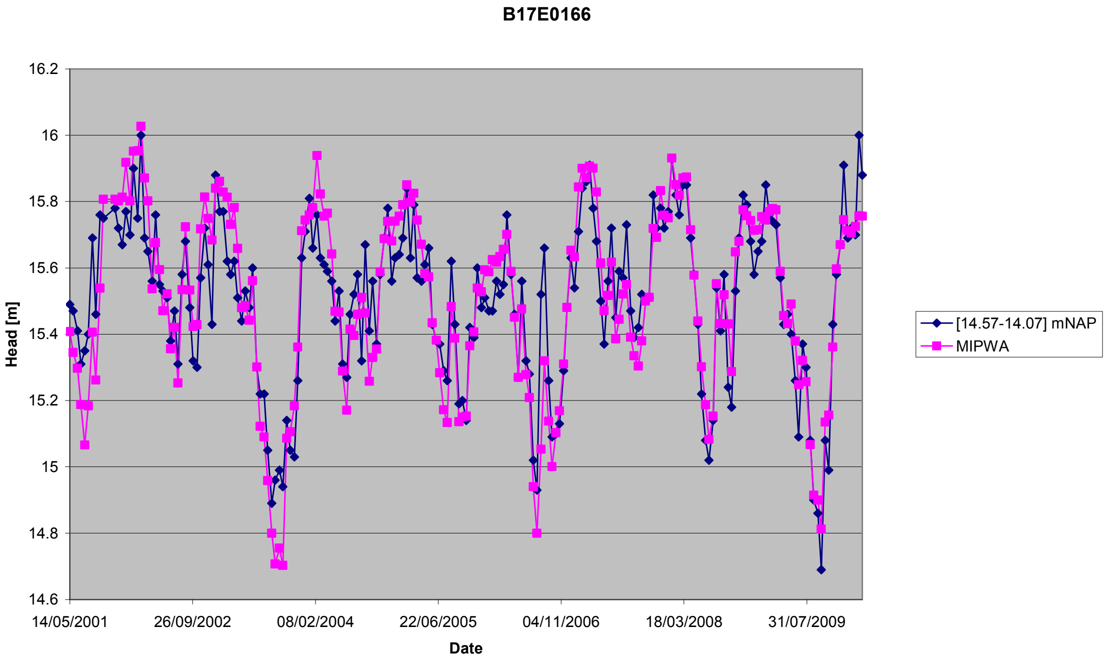


Figuur 29 Comparioson between model and B17E0086 filter 5

So the head is constantly calculated to low, this could mean that the resistance of the Peelo layer is still overestimated in this area despite the removal of the Peelo clay in the model. Evidence for this is seen in the borehole at the same location, Figure III4. The profile consist almost only the formation of Urk. This formation is known for it's coarse and gravel like character, this implies a low resistance to groundwater flow. This can also been seen if we compare the lower filter with the upper filter of the monitoring well. Between these filter there is a height difference of $53m$, if we look what the head difference between the filters it only varies between $-0.03m$ and $0.02m$ with a mean of $-0.002m$. This also indicates merely any vertical resistance. If we look at a deep borehole $400m$ to the south, Figure III 5, there is no evidence of any coarse sand. Here sands of the Peelo formation are found again. In the area of the boreholes there is a salt dome. Due to high pressure deep on deep salt layers they liquefy and push deep layer to the surface. This causes the subsurface to be unpredictable and it may vary from place to place. Because there could not be found any more evidence about the spread of the Urk formation there was decided not to further adjust the vertical resistance to improver predictions at this location.

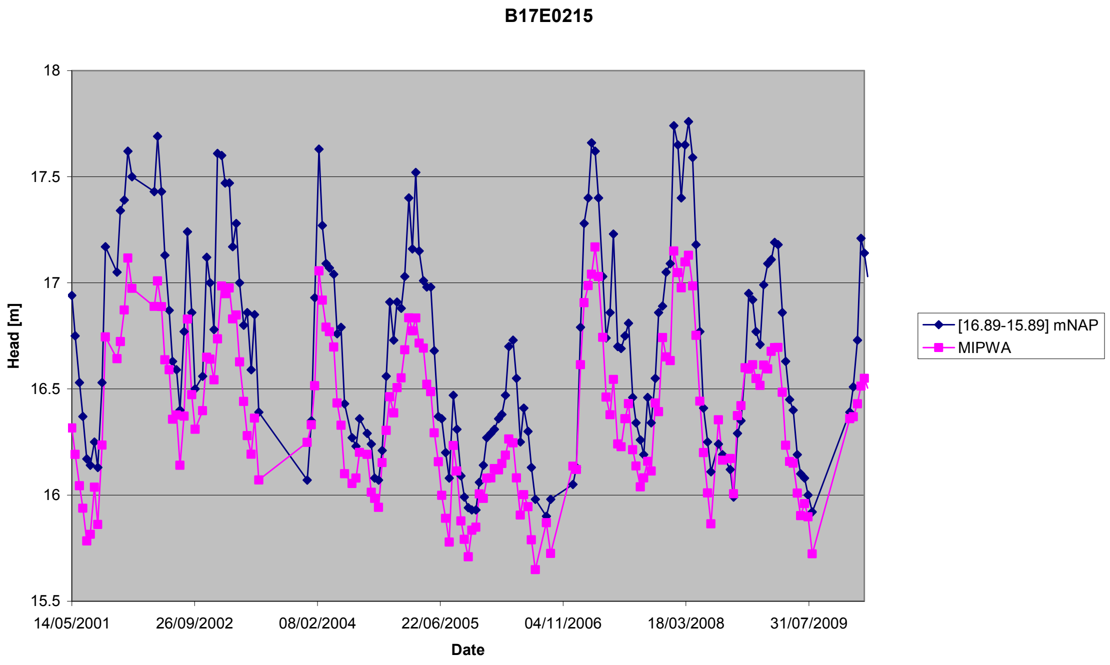
Middle deep groundwater

In the layer beneath the clay the further analysis of the predictions will concentrate on a smaller area, Figure III 6, here 26 of the 40 monitoring wells are predicted within the $\pm 0.15m$ margin. The predictions are especially good in the Elperstroom. For instance; B17E0166;



Figuur 30 Comparison between model and B17E0166

It can be seen that the minima and maxima are not always predicted good. Some time they are overestimated and other times under estimated. The overall predictions are nevertheless good. On the east flank the predictions are less accurate, here the mean differences is $-0.41m$, the time serie looks as follow;



Figuur 31 Comparison between model and B17E0215

If we look at the interpolated resistance of the clay layer, Figure I 10 it can be seen that there are some “holes” in the layer near the monitoring well. This means that there is probably a path with less resistance straight through the clay (short circuit), meaning that the current resistance is overestimated. Another explanation is that the deep groundwater is predicted to low. This can be seen since the model results are structural lower. There was chosen not to change the resistance, since other locations (more important) are predicted accurate.

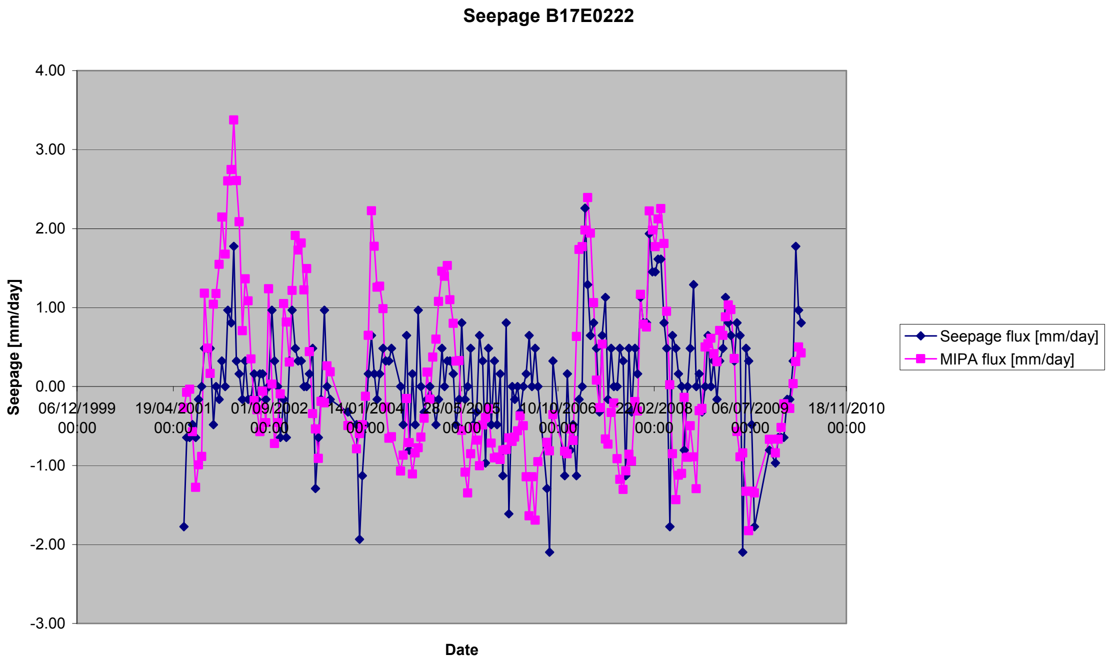
Phreatic groundwater
Next the layer above the clay; here 11 of the 25 monitoring wells are in acceptable error regime, from which most in and around the Elperstroom, Figure III 7. It can be seen that to the south-east there are several monitoring wells that make to low predictions. This is also the case for the monitoring wells beneath the clay in that area. Since both layers are predicted to low this could indicate that the groundwater recharge in that area not modelled correctly. This is supported by the facts that in this area to large lakes are located. The interaction is probably not realistically modelled.

5.3.2 Mean lowest and highest groundwater levels

The model result where further validated using the mean lowest and highest groundwater levels of the shallow monitoring wells. These where compared to the mean highest and lowest levels of the monitoring wells, Figure III 9 and III 10. It can be seen that the differences seen in the mean highest levels are not that different from the differences in the mean level. However in the mean lowest levels the differences are higher. It can be seen that in and around the Reitma the error is high and that the lowest groundwater are predicted to low. This means that the groundwater levels during the summer drop too much compared to reality and thus predicting to dry conditions. This may suggest a too low resistance of the boulder clay and a too large drainage by the surface water.

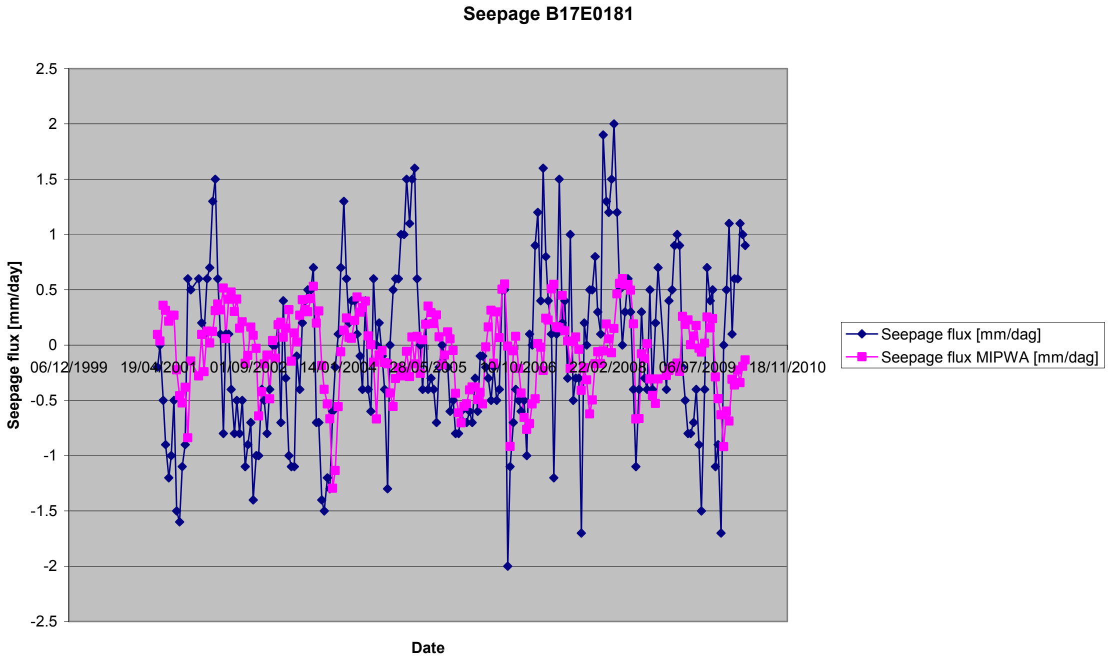
5.3.3 Upwards seepage

Since upwards seepage is such an important factor for the habitat types the predictions of the seepage trough the clay layer is investigated. Two monitoring wells were selected which have filters both under and above the clay layer, Figure III 8. Firstly B17E0222; located on the east flank of the Elperstroom; here seepage over the boulder clay is measured.



In this graph the seepage to the surface predicted by the model is compared with the measurements. A positive seepage indicates an upwards seepage and visa versa. It can be seen that most of the peaks in the seepage are predicted by the model, however the minima are a less good predicted. What is mainly striking is that the predictions are become more accurate after 2005. This is as expected since after this period a lot is changed due to the management plan. The model is calibrated on the situation after the changes of the plan, so predictions should be best for this situation. In the predictions it can be seen that there is a seasonal variation in the seepage. In the measurements this seasonal effect is less clear an there are also variations with a higher frequency. However is we compare the mean seepage there is hardly any difference, $0.08\,mm/day$ and $0.09\,mm/day$ for respectively the measurements and predictions.

Secondly, B17E0181 near the main water course bordering the Reitma;



Here the opposite is seen in the amplitude, which is much higher for the measurements. This is seen in the variance, $0.60\, mm/day$ and $0{,}13\, mm/day$ for respectively the measurements and predictions. Again the mean seepage is more or less the same, $-0.06\, mm/day$ and $-0{,}07\, mm/day$. Another feature is that the peaks in the predictions do not always coincide with the peaks found in the measurements. It is difficult to say what exactly causes these differences. It could be for instances that the resistance of the clay layer is to high. Another error could be caused by the conductance of the waterway. The monitoring well is B17E0181 is almost next to a large waterway, which cuts trough the clay layer. If the conductance of the waterway is predicted to high, the head in the layer 1 and 2 will be influenced too much by the waterway. This means that the head in the layer will almost follow the water level in the water way. Since the head beneath and above the clay layer will then almost be the same there will only be a small head difference over the clay layer and thus less seepage. Also measuring error should be considered. The monitoring wells are measured with the hand so a small mistake in measuring is imaginable. The problem in this is that the differences in head between layers is sometimes less then 0.01 m, error of the same order can easily occur when measuring by hand.

5.4 Sensitivity analysis

To see how variations in the input parameters influence predicted upwards seepage to the surface a sensitivity analysis was done. Here different parameters where are varied to see how this affectes the upwards seepage. To do this a point in the Reitma was chosen which represents typical conditions. Then 12 model runs were done where in each run a different parameter was changed. For each run the time series of the representative point was compared to the calibrated model. This resulted in the following;

Parameter	**Difference [%]**
Waterway conductance + 10%	-15%
Waterway conductance - 10%	56%
Resistance clay + 10%	-8%
Resistance clay - 10%	34%
Resistance Peelo + 10%	-4%
Resistance Peelo - 10%	4%
Infiltration capacity + 10%	0%
Infiltration capacity - 10%	-1%
Precipitation + 10%	152%
Precipitation - 10%	-158%
Evapotranspiration + 10%	-44%
Evapotranspiration - 10%	84%

It can be seen that the largest effect on the upwards seepage is given by parameters that affect the recharge of groundwater; waterway conductance, precipitation, evapotranspiration. In a less extend, bus still significant the seepage is affected by resistance of the boulder layer. This can be expected since this directly determines how “easy” the water can seep upwards. Varying the resistance of the Peelo layer only affects the upwards seepage for a small part. It should however be noted that in reality the uncertainty in resistance is much larger, since it is based on a mean conductivity and thickness. The varying of the infiltration capacity of the top soil has almost no significant effect. The only way the infiltration capacity influences the groundwater recharge is by determining when over land flow takes place. This is when the precipitation rate exceeds the infiltration capacity. In the Dutch climate such events rarely occur, so there is almost no influence on the groundwater recharge.

When analyzing the sensitivity analysis one should keep in mind that the plus and minus 10% variation has nothing to do with the accuracy of the model. For instance the uncertainty in the resistance of the Peelo clay is much larger then 10% it could easily be 100%. The sensitivity analysis merely gives insight about what the determining parameter for upwards seepage are and has nothing to do with how accurate it is predicted.

5.5 Conclusion and discussion

Despite the effort of improving some of the model parameters there is still some uncertainty in the model. Where the head in the deep subsurface is predicted accurately, the head in the shallow subsurface is predicted less accurately, Figures III 1, III 2, III3.This because in the shallow surface much more processes influence the groundwater head and each process adds a little uncertainty. In and around the Elperstroom the uncertainty in the model results are acceptable. However the there should be taken some care to what extend the predictions of the model can be used. The results can not be used as predictions of groundwater head at certain time. For this purpose the uncertainty is to large as for example can be seen in the sensitivity analysis. However in the results of the validation it can be seen that the trends in the measurements are predicted by the model. For example if we look at the upwards seepage, B17E0222, in the year 2008 the upwards seepage was higher compared to other years. In the model results this is also predicted. Concluding, it can be said that the model is not suitable to do exact predictions of groundwater levels at a certain time. It can however be used to calculate trends and changes in groundwater levels and upwards seepage due to changing external factors.

6 Model results

In this Chapter the effect of certain proposed land use changes will be presented and discussed. The effect on the upwards seepage and the mean, mean highest, mean lowest and mean spring water levels will be investigated and compared to the different requirements discussed in Section 2.2. In the Figures in appendix VI the results of the different model runs are shown, which consist of:

- Mean groundwater head of layer 1, 2 and 4, with groundwater streamlines under the Reitma.
- Mean seepage to layer 1 and 3.
- Mean highest and lowest groundwater level
- Suitable area for Molinia meadows and alkaline fens.
- Differences between current situation and proposed scenarios for; mean highest and lowest groundwater level, seepage layer 1 and 4, groundwater head in layer 1,2 and 4.

6.1 Current situation

In this Section the model was used to calculate the different parameters with the conditions as they are now in and around the Reitma, the calibrated model. The model was run from 14/1/2001 to 28/4/2010; Figure VI 2 to VI 11.

6.1.1 Results

Based on the habitat type criteria in section 2.2 it was found that the suitable area for Molinia meadows is 8.0 ha in the Elperstroom area. (There area no areas which meet all the criteria for the alkaline fens. The main restricting criterion is the mean lowest groundwater level which is 0.84 m beneath surface in the Reitma and the alkaline fens require 0.3 m beneath surface level. As discussed in chapter 5, during the validation in was noticed that the lowest groundwater levels are predicted too low. So due to the high error the criterion is omitted) Most of the suitable areas are not found at locations where the vegetation is found in the Reitma, this will be discussed later on. From the streamlines of layer 4 it can be seen that the deep groundwater flow under the Reitma originates from the west flank and bends to the south-east and is concentrated in a small band. The groundwater in layer 2 has a much larger band from which it originates on the west flank. The larger influence of the low water levels in the water ways is also seen clearly, since all the streamlines end up in these waterways. For the analysis of the effects a representative point was chosen in the Reitma where there area alkaline fens in the current situation. The seepage to the first layer is 0.11 mm/day; the areas of highest seepage are located in the north of the Reitma. Again here the large influence of the waterways east and south of the Reitma can, here a high seepage is seen to the waterways and the agricultural land to the south. For the upwards seepage from the calcareous layers the highest fluxes area concentrated to the south of the Reitma, under the agricultural area. The upwards seepage at the representative point is 0.27 mm/day.

6.2 Scenario 1

In the last years the terrain managers (Staatsbosbeheer) made an effort to purchase different agricultural lands surrounding the Elperstroom. This was done with the idea that these lands could be managed in such a way that it would be profitable for the habitat types in the Elperstroom. In this scenario the effect of managing the agricultural lands, 84 ha, on the east flank will be investigated, Figure VI 1. In this scenario it is assumed that the groundwater levels in this area do not have to be managed. So there is no need for drainage, irrigation and waterways. Accordingly these where turned off in the selected area, this included the large waterway on the east flank of the Reitma. Since there are no waterways all the precipitation will infiltrate, this means that there will be no drainage of inundated water due to overland flow to the waterways. To ensure this condition is met the overland flow is “turned off”. The results are shown in Figure VI 12 to VI 28.

6.2.1 Results

In this scenario the suitable area for Molinia meadows has increased to 10.8 ha and the area for alkaline fens to 4.0 ha (without mean lowest groundwater level criterion). Especially in the Reitma a lot of suitable area is created suitable for Molinia meadows. It can be seen that the effect of the scenario is mainly concentrated on the agricultural lands where the measure are taken, from there it radiates out. Due to extra groundwater recharge in the area, the mean head of the first layer is 0.01 m higher in the Reitma compared to the current situation. The mean lowest is approximately 0.02 cm higher and the mean highest did not change. The effect in the deeper layers 2 and 4 is higher; respectively 0.03 and 0.04 m. From the seepage results and the streamlines it can be seen why this is the case. The supply of groundwater to layer 2 and 4 run directly under the changed agricultural lands. In this scenario more water infiltrates in the agricultural land from the surface to layer 2 and 4, since this water flow to the Reitma the head will also rise in this area. In turn this will cause an increased seepage from the layer 2 to the surface. The increased seepage will also raise the groundwater levels in the Reitma but in a less extend then the underlying layers since the effect is demped by the clay layer and the intense network of shallow waterways drain a lot of water. The seepage to the surface in this scenario has a mean of 0.18 mm/day so is almost doubled compared to the current situation. The seepage from the deep layer also increased to 0.32 mm/day. It can be seen that on the west-side of the Reitma the deep seepage increased compared to the current situation, however on the east-side a larger part is seen where the seepage decreases. It can also be seen that not only the Elperstroom is affected but also in other surrounding areas. In almost the whole forest area east of the Elperstroom the water level in the first layer is increased by approximately 1 cm, to the west and north-west in some agricultural lands an increase of the same order is seen.

6.3 Scenario 2

In the agricultural lands to the south of the Reitma, Staatsbosbeheer also purchased some small lands. Here again as in scenario 1 in the area depicted in Figure VI 1 all the water managing factors are turned off. The total area affected by the measures is 111 ha, from this total area only a smaller part is purchased by the terrain managers. The results are shown in Figure VI 29 to VI 45.

6.3.1 Results

When scenario 2 is modelled the area suitable for Molinia meadows increase to 11.9 ha and for alkaline fens it decreases to 3.1 ha. At the representative point the groundwater levels increased, the mean with 0.01 m, the mean lowest with 0.09m and the highest did not change.. This increase is caused by the fact that normally a larger part of the groundwater in these layers seeps to the surface water in the Grevema. In this scenario however it can be seen that the seepage decreased in the the Grevema. The waterways with low water levels are removed so the groundwater “stays” in the deeper layers causing the head to increase. The decreased upward seepage to the surface also causes the head in the deeper layers to increase, both in layer 2 and 4 the head increased with 0.09 cm. Because of the higher head in the deeper layers the seepage to the surface will, which increased with 0.21 mm/day. The seepage from the deep underground to the middle deep merely changed, this is as expected since the head in layer 2 and 4 increased with the same amount. Also in this scenario in can be seen that there is also a larger effect on the forest and the agricultural lands.

6.4 Scenario 3

As mentioned in the introduction in the beginning of the 20th century almost all the heath on the east flank was transformed to production forest. These woodlands evaporate a much larger amount of water then heath, so the groundwater recharge will be a lot less. In contrast to the scenarios where only agricultural lands are affected in this scenario the woodlands will be affected. In this scenario all the woodlands were transformed to heath, Figure VI 1. The area affected by the scenario is approximately 815 ha, it consist of 60% deciduous and 40% coniferous trees. To model this scenario in the land-use map all the deciduous and coniferous trees were changed to heath. Accordingly CAPSIM will translate this to a precipitation loss, evepotranpiration and infiltration capacity appropriate for heath. The results are shown in Figure VI 46 to VI 62.

6.4.1 Results

In scenario 3 the suitable area for Molinia meadows increased to 14.9 ha and for alkaline fens to 5.3 ha. The impact on the groundwater head of the different layers under the Reitma is an increase of the head; 0.01 m for layer 1, 0.03 m for layer 2 and 0.04 m for layer 4. Again as in scenario 1 the largest impact is on the layer 2 and 4 since these are directly influenced by the extra groundwater recharge of heath compared to forest. The increased head in these layers cause the seepage to the Reitma to increase. For the seepage from the deep layer an increase of 0.09 mm/day is seen and for the seepage to the surface an increase of 0.07 mm/day. The increased seepage causes the groundwater levels to rise in the Reitma, the mean lowest is 0.80 m and the highest 0.06 m. It can be seen that the largest effects can be seen in the Oosterma, the upper part of the Reitma. However apart from the Elperstroom, large area of agricultural land are influenced.

6.5 Scenario 4

In the last scenario it is investigated whether it would be useful to manage a small patch of agricultural land as described in scenario 1 and 2, the area is 14.5 ha. Since the agricultural lands do not have to be drained any more there is no need for low water levels in the waterway west of the Elperstroom. So the water levels are raised, because of the higher water level the bottom of the water way can also be raised so it will not cut trough the clay layer anymore. The results are shown in Figure VI 63 to VI 78.

6.5.1 Results

In this scenario the suitable area for Molinia meadows increased to 8.8 ha and for alkaline fens to 3.9. It can be seen that in the changed agricultural land the infiltration in is increased by an amount of 0.4 mm/day. It can also be seen from the streamlines in the second layer that effect of the large waterway decreased; now the streamlines do end up in the waterways in the Grevema. The effect of this scenario on the groundwater is concentrated on the east of the Reitma near the affected area. Since the effects are so concentrated the mean change of the groundwater levels in the Reitma area almost insignificant, about 0.01 m. There is however an effect measured in the deeper layers, the head in layer 2 increased with 0.05 m and the head in layer 4 slightly decreased with 0.01 m. This is due to the increased infiltration in the affected land, the head in layer 2 increased slightly more compared to layer 1 and 4. This cause the seepage to the surface to increase with 0.09 mm/day and the deep seepage decreased with 0.12 mm/day.

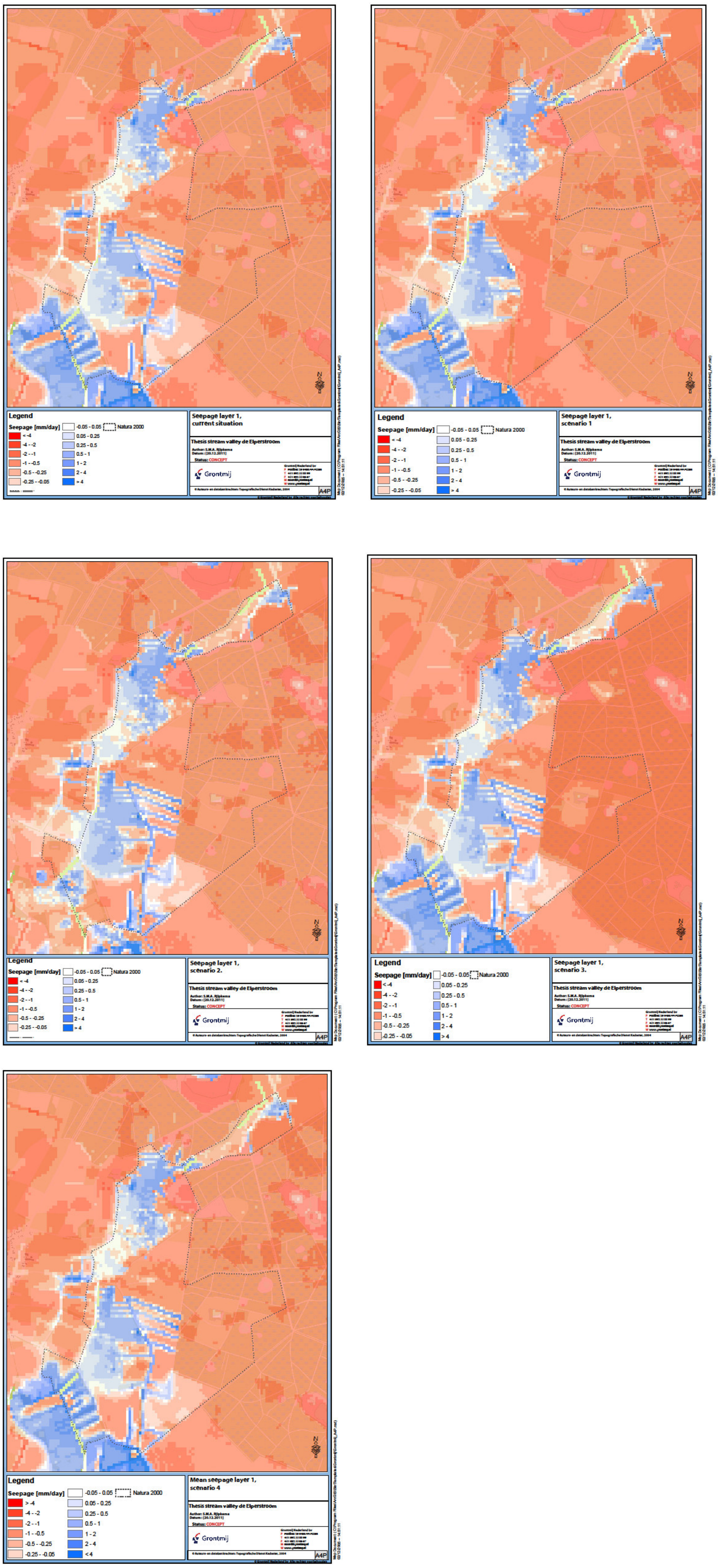
6.6 Summary

In the Table below a summary of the result for the different management scenarios is given, the numbers given are in a point chose on the location of the only Alkaline fens left in the Elperstroom, see figure 4.

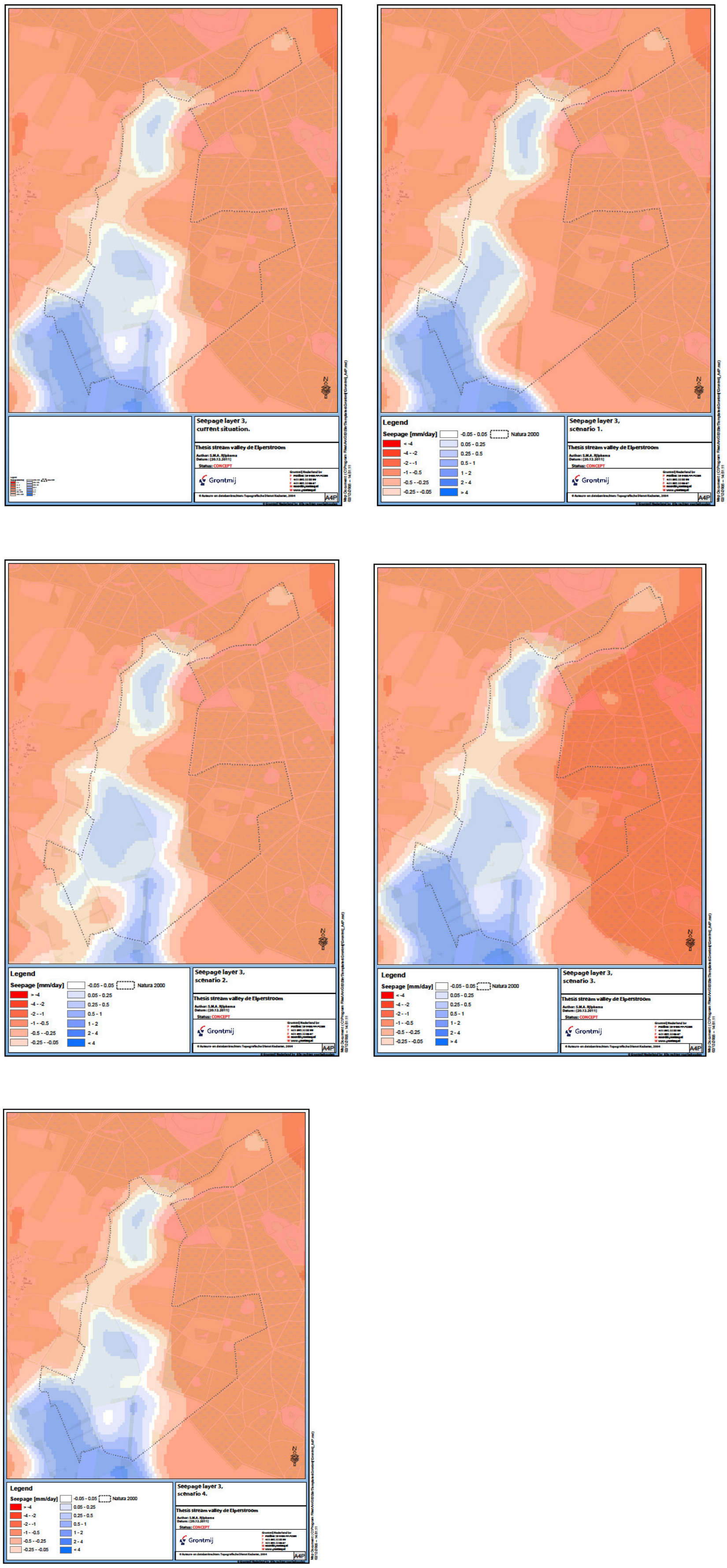
Scenario	**0**	**1**	**2**	**3**	**4**
Head layer 1 [m N.A.P.]	15.40	15.41	15.44	15.41	15.41
Head layer 2 [m N.A.P.]	15.42	15.45	15.51	15.45	15.47
Head layer 4 [m N.A.P.]	15.46	15.50	15.55	15.50	15.45
GG [m beneath surface]	0.29	0.28	0.25	0.28	0.28
GHG [m beneath surface]	0.00	0.00	0.00	0.00	0.00
GLG [m beneath surface]	0.76	0.74	0.67	0.73	0.74
Mean seepage layer 1 [mm/day]	0.11	0.18	0.32	0.17	0.20

Mean seepage layer 3 [mm/day]	0.27	0.32	0.24	0.36	0.15
Ratio seepage layer 1/layer3 [-]	0.39	0.56	1.34	0.49	1.34
Difference head layer 1 [m N.A.P.]	N/A	0.01	0.04	0.01	0.01
Difference head layer 2 [m N.A.P.]	N/A	0.03	0.09	0.03	0.05
Difference head layer 4 [m N.A.P.]	N/A	0.04	0.09	0.04	-0.01
Difference GG [m beneath surface]	N/A	0.01	0.04	0.01	0.01
Difference GHG [m beneath surface]	N/A	0.00	0.00	0.00	0.00
Difference GLG [m beneath surface]	N/A	0.02	0.09	0.03	0.01
Difference seepage layer 1 [mm/day]	N/A	0.07	0.21	0.07	0.09
Difference seepage layer 3 [mm/day]	N/A	0.05	-0.03	0.09	-0.12
Difference GG [%]	N/A	3.70	15.29	4.25	3.39
Difference GHG [%]	N/A	-12.20	41.49	17.07	36.59
Difference GLG [%]	N/A	2.58	11.39	3.40	1.90
Difference seepage layer 1 [%]	N/A	69.95	197.11	63.70	83.48
Difference seepage layer 3 [%]	N/A	19.86	-12.59	32.93	-45.88
Affected area [ha]	N/A	84.00	111.10	815.80	14.50
Difference GG per change area [% / ha]	N/A	0.04	0.14	0.005	0.23
Difference GLG per change area [% / ha]	N/A	0.03	0.10	0.004	0.13
Difference GK1 per change area [% / ha]	N/A	0.83	1.77	0.08	5.76
Difference GK3 per change area [% / ha]	N/A	0.24	-0.11	0.04	-3.16

However there are large spatial differences in the effects. This is illustrated in the figure 32 and 33. Here it can be seen that the effect of scenario 1 and 4 are mainly located on the lower part of the Elperstroom. Scenario 3 has besides an effect on the Reitma also en large effect on the upper part of the Elperstroom. Wheras the second scenario the effects are mainly located to the south of the Elperstroom.



Figuur 32 Upwards seepage to first layer, for the different scenarios (from left to right form top to bottom), current situation, scenario 1, 2, 3, 4.



Figuur 33 Upwards seepage to third layer, for the different scenarios (from left to right form top to bottom), current situation, scenario 1, 2, 3, 4.

6.7 Discussion

When analyzing the model results some comments can be made on the significance of the model results. As a rule of thumb is that a change of head less then 0.05 m is considered as no change. If this rule of thumb is however applied to the seepage in the Elperstroom, where the resistance of the boulder clay is on average 100 days, a change of seepage of 0.5 mm/day should the be considered as no change. However all the effects seen in the model are within these margins and should accordingly be considered as no effect. This shows the difficulty in calculating effects on seepage. The effects on the seepage are so small that they are of the same order or even smaller than the errors occurring due to model uncertainty, as could be seen in the sensitivity analysis. This means that statements with respect to absolute amount of seepage are impossible to do based on the model results. The model can however be used to describe the relative effectiveness and efficiency of the scenarios.

Another error in the model is the structural over prediction of the mean lowest groundwater level. This is a known problem in MIPWA and it is not sure what causes this. Since this effect is only seen in the upper layer it has something to do with the interaction between the groundwater and the surface and/or unsaturated zone. There is also evidence that the overland flow is causing lower levels. In this research all the inundated water above 0.02m will “leave” the model. This is why in the effects the highest groundwater level merely changes because in the Reitma the water is already at the 0.02 m boundary. Whereas is we look at the reality there are parts of the Reitma where water inundates more then 0.1 m during winter. When during the spring and summer precipitation decreases, this water in reality infiltrate whereas in the model the water leaves the model, causing water levels to be modelled to low. Another cause may be the poor accuracy of the conductance of the waterways. These are based on expert judgement combined with a field study. The conductance may be predicted to high so too much water will leave the model through the surface water. Because of this, now the mean lowest groundwater levels are not taken in consideration when determining suitable areas

7 Conclusions & discussion

7.1 Conclusion

The current groundwater management of the Reitma is unsustainable for conservation and restoration of the habitat types for Molinia meadows and alkaline fens. There are two criteria which cause this. Firstly the mean lowest groundwater levels, from monitoring wells it was seen that groundwater levels drop from 0.48 m to even 0.95 m in extreme cases. The low water levels cause high aerobic conditions in the phreatic aquifer. Because in the Reitma there is peat present the aerobic conditions will increase mineralization of the soil causing it to become eutrophic. Secondly the low upwards seepage, since upwards seepage passes through several calcareous layers before it comes in the Reitma the seepage will be alkaline and will have high levels of iron and calcium. The alkaline conditions slow down the process of mineralization and the nutrients created are immobilized by the iron and calcium. The current amount of seepage is entering the Reitma is not enough to compensate the effect of mineralization, especially with the low water levels in the summer. This is why over the last decades the areas of Molinia meadows and alkaline fens are decreased to a few small patches. To firstly restore and secondly sustainably protect the habitat types the Reitma and especially the surrounding lands should be designed and managed in such a way that it is favourable for the habitat types.

In general it was found that the different scenarios mainly effected the the seepage in the Reitma and in a less extend the groundwater levels in the phreatic aquifer. Partly this is due to model inaccuracy and part due to the intense network of trenches and ditches which drain a lot of phreatic water from the area. For the scenarios it was found that the waterlevels increased in the order of 0.01 m where as changes in the order of 0.1 are needed. In scenario 1 it was seen that the seepage to the surface increased in the whole Reitma whereas the deep seepage decreased for a large part. So the seepage to the area increased but the composition also changed to a more acidic type this is not favourable for the habitat types. With respect to the groundwater levels it was found that the increase was highest in the east flank of the Reitma. There are also effects seen on the west-flank in the agricultural area and in the forest area in the east. With this model it is difficult to say if the effect is enough to damage the forest or agricultural land. Firstly, because the model is not accurate enough and secondly, because to investigate the effect more information is needed about the exact composition of the agricultural land and forest. With respect to realizing this scenario, this scenario is relatively easy. Large part of the lands are already purchased, however some effort should still be done to remove the waterways and investigated the effects on the agricultural lands.

In scenario 2 it was found that again the largest effect is seen in the changed area it self. Both the seepage to the surface and the deep seepage increased both with approximately with the same amount. In a small part in the south of the Reitma the surface seepage increased more then the deep acidifying the seepage. From the model results it was seen that the seepage also increased in other parts of the Elperstroom. In this scenario the groundwater level increased the most compared to the other scenarios. However there is also an increase in large parts to the east and west of the whole Elperstroom between 0.01 m and 0.10 m. In this scenario the effect on area besides the Elperstroom is much larger then scenario 1. With respect to realizing, larger parts of the agricultural lands still have to be purchased making this scenario less easy to realize.

In scenario 3 it was seen that this scenario affects the largest area. In the whole Elperstroom the groundwater levels rise about 0.01 m and parts where it is even 0.05 m. The same is true for the seepage in the Reitma. There is a large increase in both the surface and deep seepage.

The largest increases are seen in the north of the Elperstroom. The side-effects of this scenario are verry large. In almost all the surrounding lands there area effects seen on the groundwater levels and upwards seepage. This make the realization of this scenario also difficult, because there needs to be clarity on these effects. Another point is the larger effort it would take to realize the scenario, this would mean cutting down 815 ha of woodlands.

Scenaio 4 is the smallest of them all, making it the most easy to realize. The effect is localized to the west of the Reitma, where the head slightly increases. The seepage increases over a larger area along the west flank. The deep seepage decreased, making the surface seepage more acidic.

7.2 Discussion

For future use of the model some suggestions can be done to improve the model results. First the Peelo formation, in this formation there is al lot of uncertainty with respect to the resistance and the exact thickness. In the model the resistance is based on an average thickness and hydraulic conductivity, this causes a large uncertainty in the calcareous upwards seepage to the Reitma. This is however an important parameter for the protection of the habitat types. To improve the accuracy of the resistance, further investigation of the deep boreholes should be done and where needed especially around the Elperstroom additional boreholes should be placed.

Another improvement would be to additionally calibrate the model with water balances of the Reitma. A water balance is a balance between al the water that comes in the area (precipitation, upwards seepage, irrigation and infiltration from surface water) and goes out (groundwater infiltration, drainage by surface water, overland flow and artificial drainage). The accuracy of the conductance of the waterways could be improved in this way. From the model results it is known how much water leaves the model through the waterways, if this is then compared with discharge measurements of the Reitma the conductance can be improved. However there are no measurements of the discharge from the Reitma and a measure weir should be installed to get the information.

Since the upwards seepage is such an important parameter for the habitat types the model should also be calibrated on direct measurements of the seepage. In the Elperstroom itself only one monitoring well was found that provided information about the seepage, this was only used in the thesis to validate the model. It would be better to have a good idea of what the current situation is with respect to the upwards seepage. This could be done with additional placement of monitoring wells under and above the Holocene sediments. Better would be to have an area covering map of the upwards seepage, this could be made using new measuring techniques which make use of the groundwater chemical signature to determine the upwards seepage. This information could then be used to further calibrate the model parameters.

Besides effort in improving the model there are some aspects which where not considered in this Thesis but could be interesting for further research. The requirements for the habitats types are also some what uncertain and arbitrary. It is difficult to say what the exact amount of upwards seepage is for a suitable habitat especially on a year average. There are reports that say that it is enough that for a short period of time there is a high amount of upwards seepage to recharge the cation-complex and that this is enough to buffer the less suitable groundwater the rest of the time. This makes it difficult to do exact predictions about the suitable areas for the different habitats.

Another aspect that is not considered is the unsaturated zone. In an earlier research **(Romeyn, 1977)** a strong correlation between the presences of habitats and soil profile was found. In the Reitma there are roughly two soil profiles in the unsaturated zone; both profiles start with a later of peat at the surface. Next comes either a layer of sand and then boulder clay or the peat is directly on the boulder clay. In the research it was found that most of the habitats where found at locations where the peat is directly on top of the clay. The reason is that the upwards seepage will much easier be transported by capillary rise in peat then in sand. So the calcareous seepage is better available in the root zone in the case of peat directly on clay. Thus in the required upwards seepage is also less then in the case with sand. It is also known that the peat itself alters the chemical composition of the seepage favourable for the vegetation.

In this thesis the different scenarios where mainly focussed on the surrounding areas and the upwards seepage in the Reitma. However the water management in the Reitma itself is also an important factor which was not investigated in this thesis. For instance what would be the effect of raising the surface water levels in the Reitma on the groundwater levels and the upwards seepage. Another argument to further research this component is the fact that the scenarios do not have that much effect on the groundwater levels in the Reitma, in the order of centimetres due to dampening of effects. To actually really significantly change the groundwater levels, also measures should be taken in the Reitma itself. In line with this is the effect of rainwater lenses. These are lenses of rainwater that form in the phreatic aquifer and “push” the upwards seepage to the surface water. It is known that surface water has a larger effect on the dynamics of these lenses **(Schot, 2004)**

8 References

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- Ontwerp beheerplan Elperstroom NATURA 2000, **2010**

9 Acknowledgement

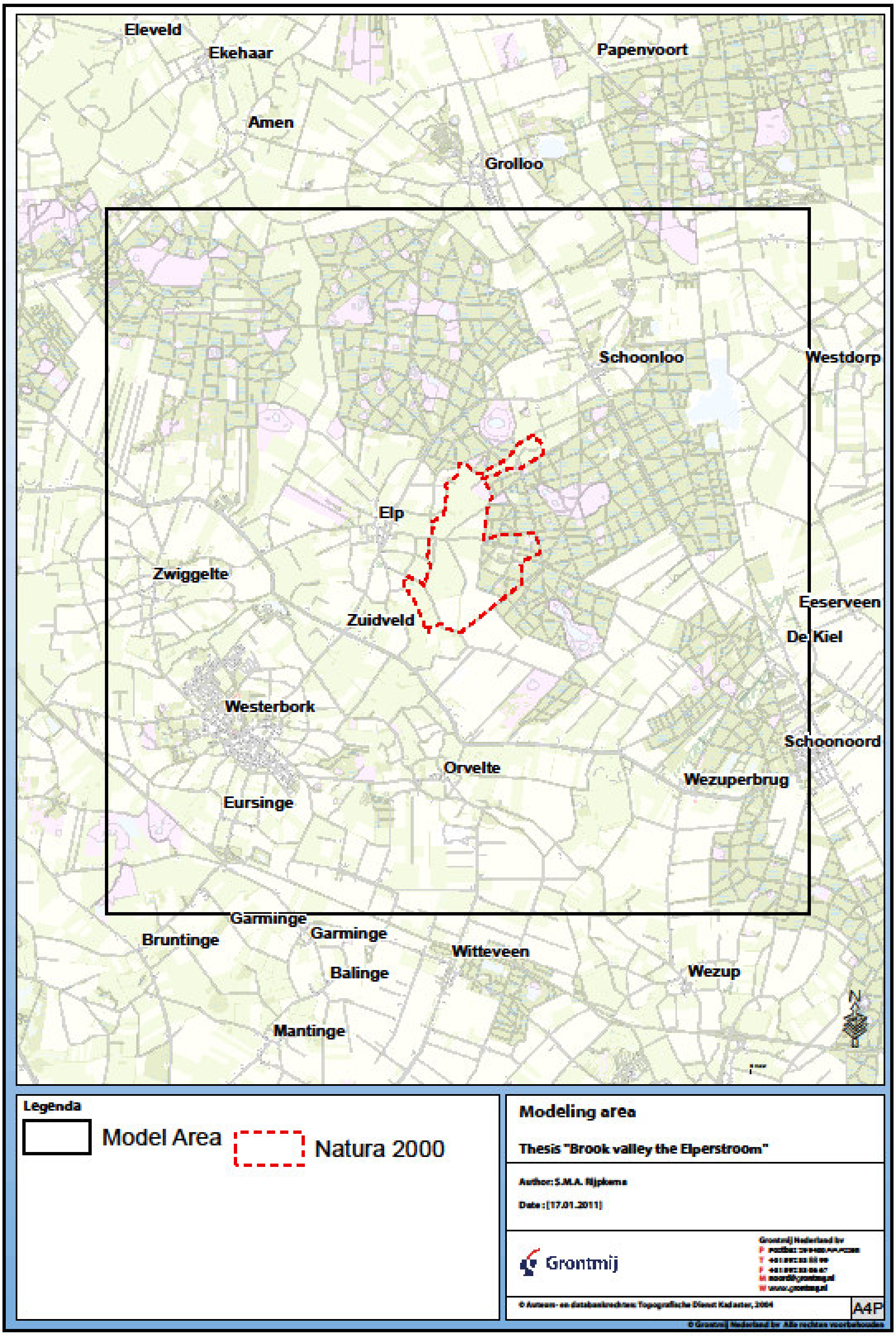
I am really thankful that Grontmij gave me the opportunity and confidence to do my thesis on this interesting subject. There was no day that I didn’t enjoy working on my thesis and saw I lot of new interesting things during the work. When I started the coupling between groundwater conditions and habitat types was fairly new to me. During my thesis I found it very interesting to find out more about this coupling and how it can be used to understand and manage different groundwater systems with respect to nature. During the thesis I also did a great deal of groundwater modelling. The main thing I learned there is how to work with a limited amount of field measurements and how this affects how one should interpret modelling results.

During my thesis I also got the chance to look at the different projects a groundwater consultant at Grontmij works on. What I really liked is the variety of projects, all with different subjects and thus all with different challenges. Another thing I liked was that most of the projects also involved consultant from other areas than only groundwater. This made me realize that I would like to pursue a career as a consultant.

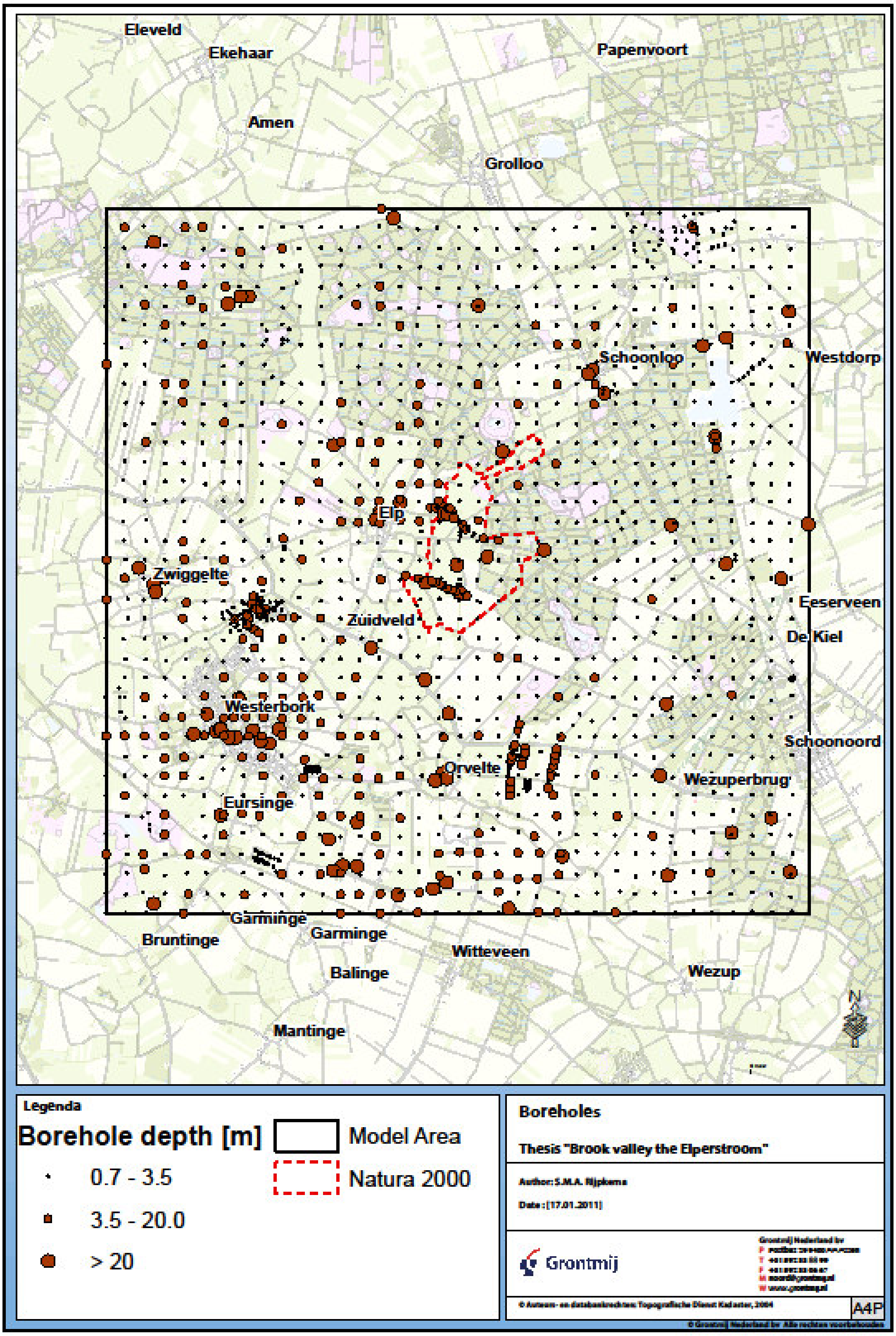
During my thesis I worked in the office in Assen. There I experienced a really pleasant working environment. Whenever I had a question about anything everybody I asked was always really willing to help, for that I am really thankful. A special thanks for Sandra Schunselaar who guided me during my thesis and with who I shared an office. We had a lot of interesting discussions which where a great input for my thesis, without her help my thesis would not come to this result.

Appendix I

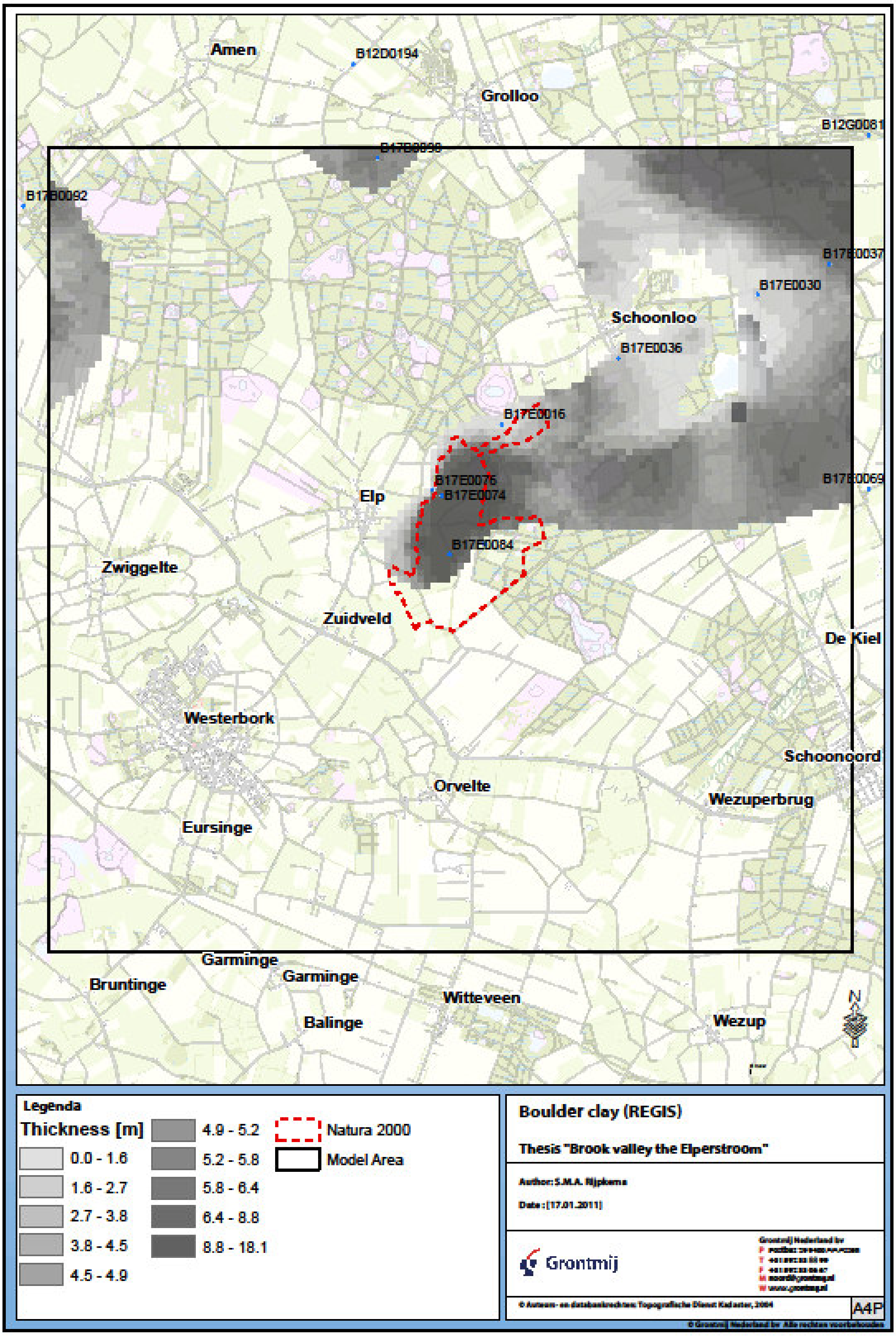
Subsurface parameters



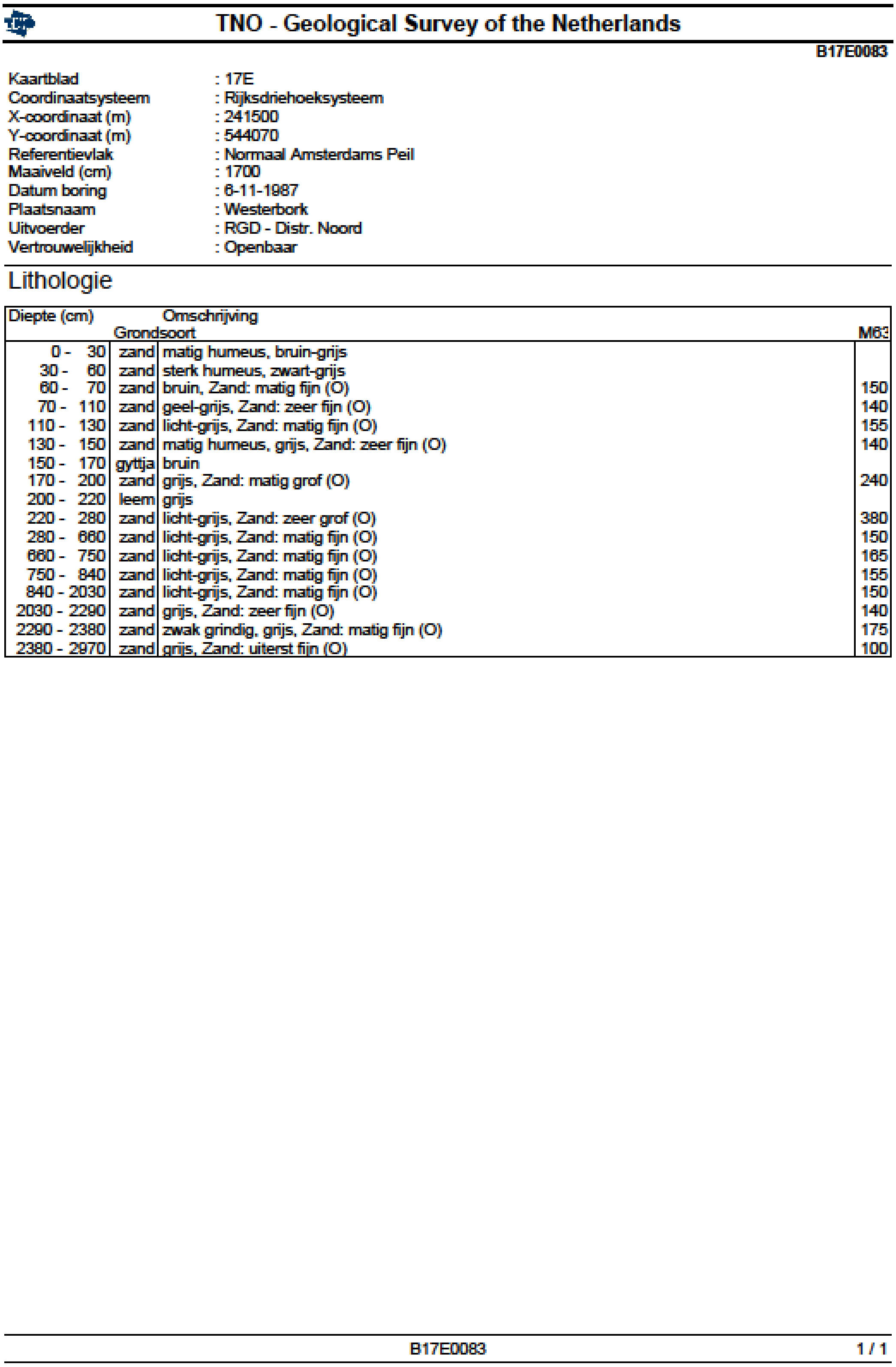
I 1 Model area



I 2 Borehole locations



I 3 Thickness Peelo clay according to REGIS



TNO - Geological Survey of the Netherlands

B17E0083

Kaartblad	: 17E
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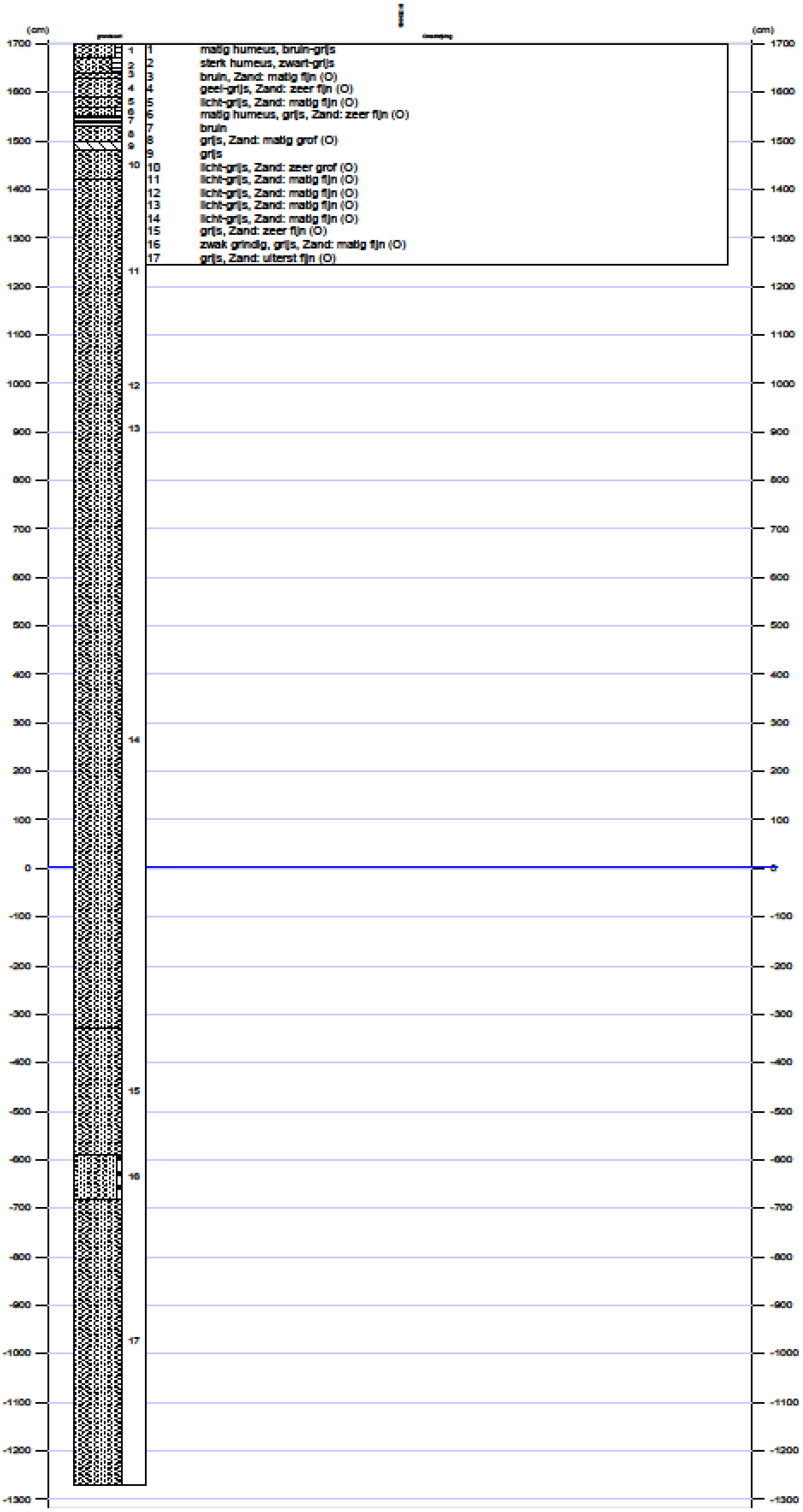
X-coordinaat (m)	: 241500
Y-coordinaat (m)	: 544070
Referentievlak	: Normaal Amsterdams Peil
Maaiveld (cm)	: 1700
Datum boring	: 6-11-1987
Plaatsnaam	: Westerbork
Uitvoerder	: RGD - Distr. Noord
Vertrouwelijkheid	: Openbaar

Lithologie

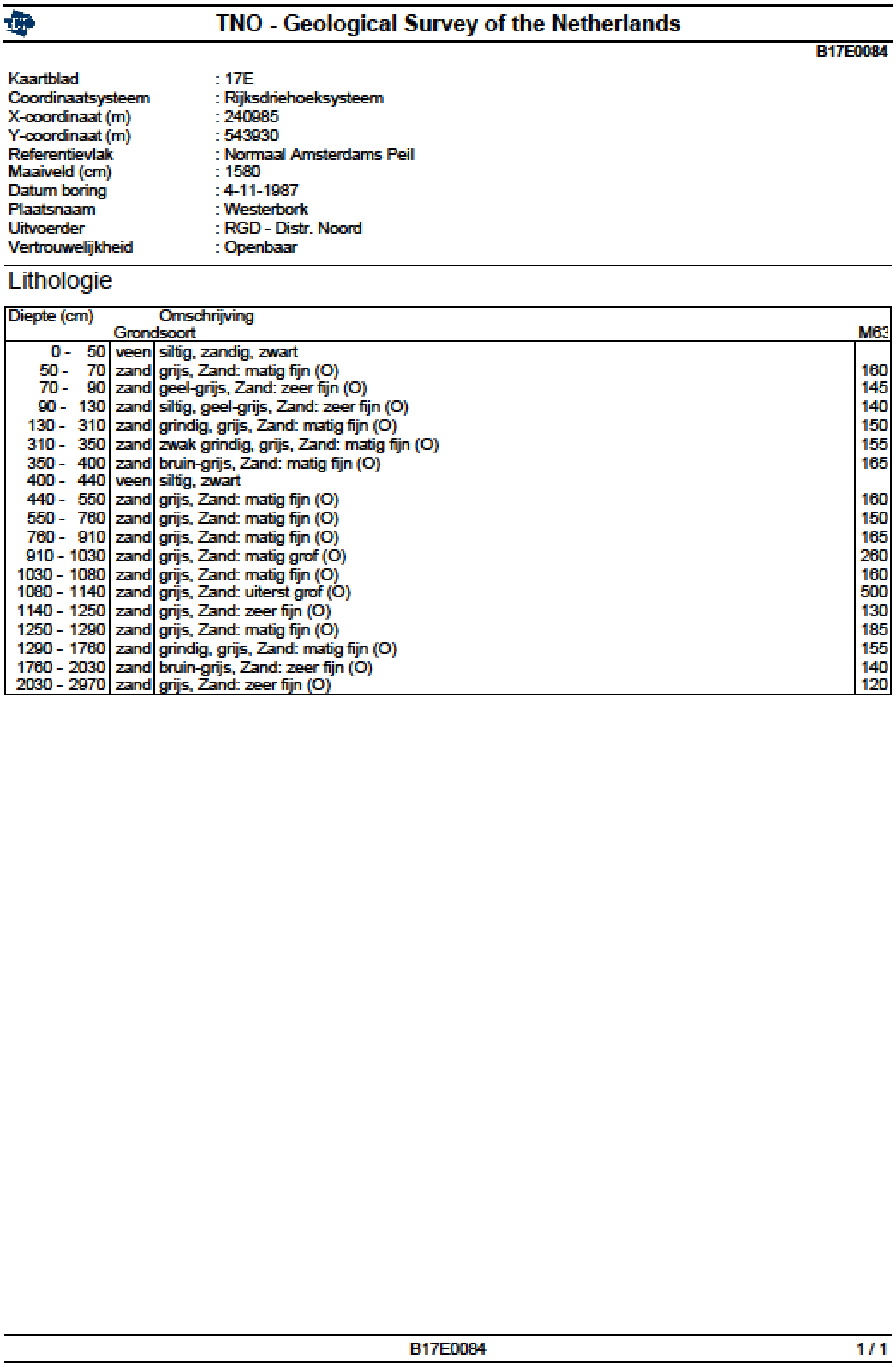
Diepte (cm)	Grondsoort	Omschrijving	M63
0 - 30	zand	matig humeus, bruin-grijs	
30 - 60	zand	sterk humeus, zwart-grijs	
60 - 70	zand	bruin, Zand: matig fijn (O)	150
70 - 110	zand	geel-grijs, Zand: zeer fijn (O)	140
110 - 130	zand	licht-grijs, Zand: matig fijn (O)	155
130 - 150	zand	matig humeus, grijs, Zand: zeer fijn (O)	140
150 - 170	gyttja	bruin	
170 - 200	zand	grijs, Zand: matig grof (O)	240
200 - 220	leem	grijs	
220 - 280	zand	licht-grijs, Zand: zeer grof (O)	380
280 - 660	zand	licht-grijs, Zand: matig fijn (O)	150
660 - 750	zand	licht-grijs, Zand: matig fijn (O)	165
750 - 840	zand	licht-grijs, Zand: matig fijn (O)	155
840 - 2030	zand	licht-grijs, Zand: matig fijn (O)	150
2030 - 2290	zand	grijs, Zand: zeer fijn (O)	140
2290 - 2380	zand	zwak grindig, grijs, Zand: matig fijn (O)	175
2380 - 2970	zand	grijs, Zand: uiterst fijn (O)	100

B17E0083 1 / 1

I 4 B17E0083 borehole log



1	matig humeus, bruin-grijs
2	sterk humeus, zwart-grijs
3	bruin, Zand: matig fijn (O)
4	geel-grijs, Zand: zeer fijn (O)
5	licht-grijs, Zand: matig fijn (O)
6	matig humeus, grijs, Zand: zeer fijn (O)
7	bruin
8	grijs, Zand: matig grof (O)
9	grijs
10	licht-grijs, Zand: zeer grof (O)
11	licht-grijs, Zand: matig fijn (O)
12	licht-grijs, Zand: matig fijn (O)
13	licht-grijs, Zand: matig fijn (O)
14	licht-grijs, Zand: matig fijn (O)
15	grijs, Zand: zeer fijn (O)
16	zwak grindig, grijs, Zand: matig fijn (O)
17	grijs, Zand: uiterst fijn (O)



TNO - Geological Survey of the Netherlands

B17E0084

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Y-coordinaat (m)	: 543930
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Maaiveld (cm)	: 1580
Datum boring	: 4-11-1987
Plaatsnaam	: Westerbork
Uitvoerder	: RGD - Distr. Noord
Vertrouwelijkheid	: Openbaar

Lithologie

Diepte (cm)	Grondsoort	Omschrijving	M63
0 - 50	veen	siltig, zandig, zwart	
50 - 70	zand	grijs, Zand: matig fijn (O)	160
70 - 90	zand	geel-grijs, Zand: zeer fijn (O)	145
90 - 130	zand	siltig, geel-grijs, Zand: zeer fijn (O)	140
130 - 310	zand	grindig, grijs, Zand: matig fijn (O)	150
310 - 350	zand	zwak grindig, grijs, Zand: matig fijn (O)	155
350 - 400	zand	bruin-grijs, Zand: matig fijn (O)	165
400 - 440	veen	siltig, zwart	
440 - 550	zand	grijs, Zand: matig fijn (O)	160
550 - 760	zand	grijs, Zand: matig fijn (O)	150
760 - 910	zand	grijs, Zand: matig fijn (O)	165
910 - 1030	zand	grijs, Zand: matig grof (O)	260
1030 - 1080	zand	grijs, Zand: matig fijn (O)	160
1080 - 1140	zand	grijs, Zand: uiterst grof (O)	500
1140 - 1250	zand	grijs, Zand: zeer fijn (O)	130
1250 - 1290	zand	grijs, Zand: matig fijn (O)	185
1290 - 1760	zand	grindig, grijs, Zand: matig fijn (O)	155
1760 - 2030	zand	bruin-grijs, Zand: zeer fijn (O)	140
2030 - 2970	zand	grijs, Zand: zeer fijn (O)	120

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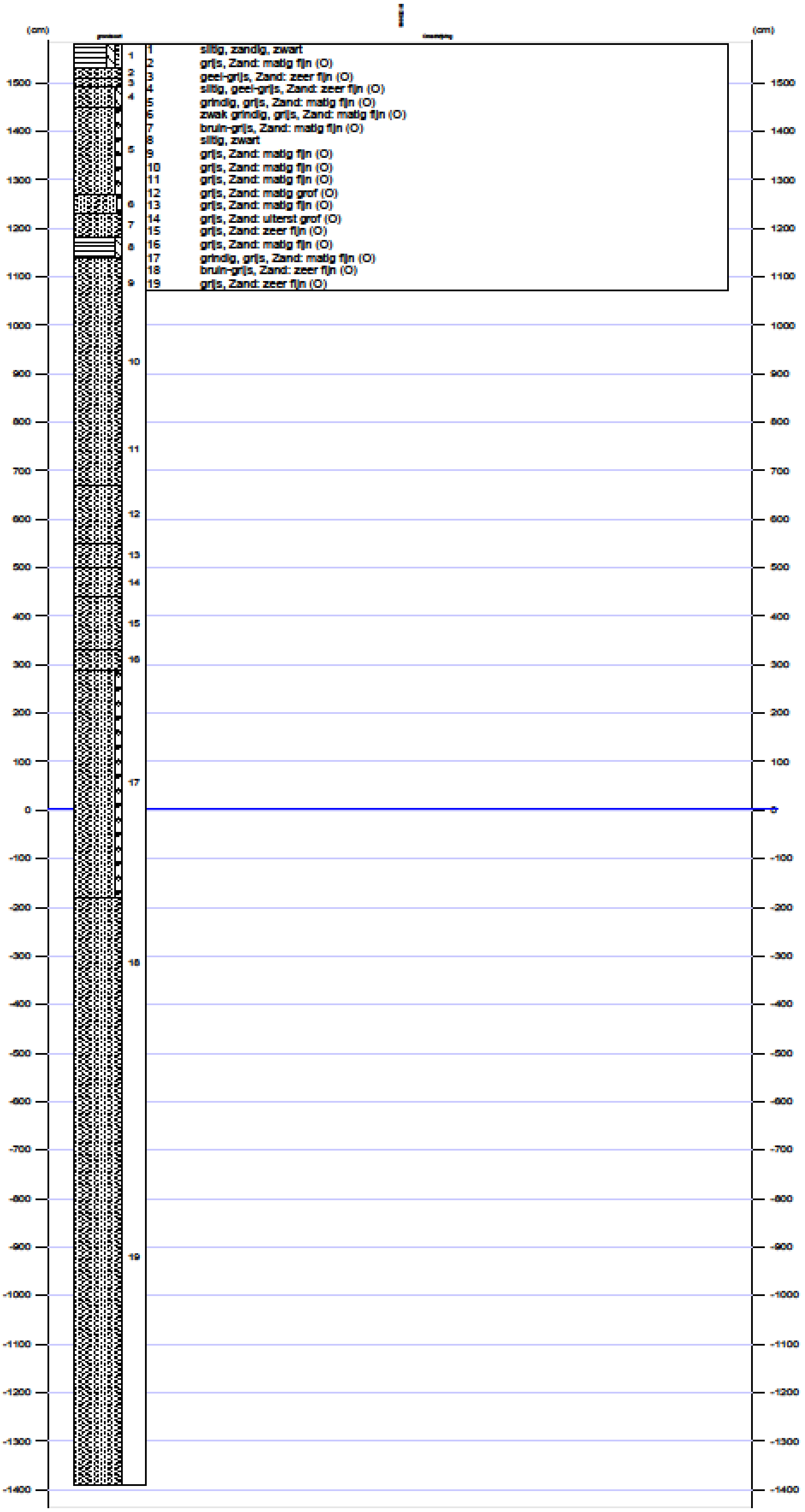
I 5 B17E0084 borehole log


(cm)
(cm)
1 siltig, zandig, zwart
2 grijs, Zand: matig fijn (O)
3 geel-grijs, Zand: zeer fijn (O)
4 siltig, geel-grijs, Zand: zeer fijn (O)
5 grindig, grijs, Zand: matig fijn (O)
6 zwak grindig, grijs, Zand: matig fijn (O)
7 bruin-grijs, Zand: matig fijn (O)
8 siltig, zwart
9 grijs, Zand: matig fijn (O)
10 grijs, Zand: matig fijn (O)
11 grijs, Zand: matig fijn (O)
12 grijs, Zand: matig grof (O)
13 grijs, Zand: matig fijn (O)
14 grijs, Zand: uiterst grof (O)
15 grijs, Zand: zeer fijn (O)
16 grijs, Zand: matig fijn (O)
17 grindig, grijs, Zand: matig fijn (O)
18 bruin-grijs, Zand: zeer fijn (O)
19 grijs, Zand: zeer fijn (O)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
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-400
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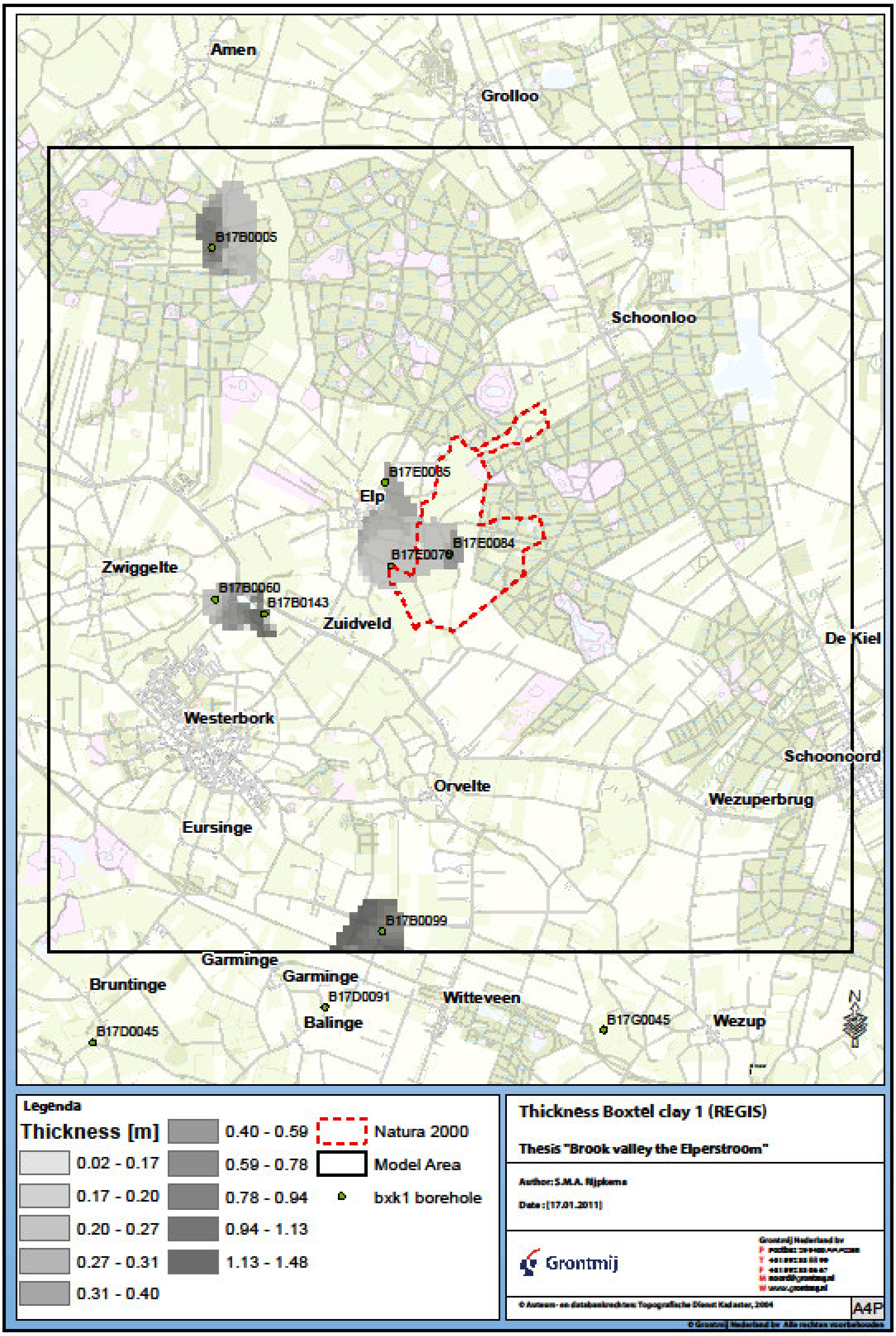
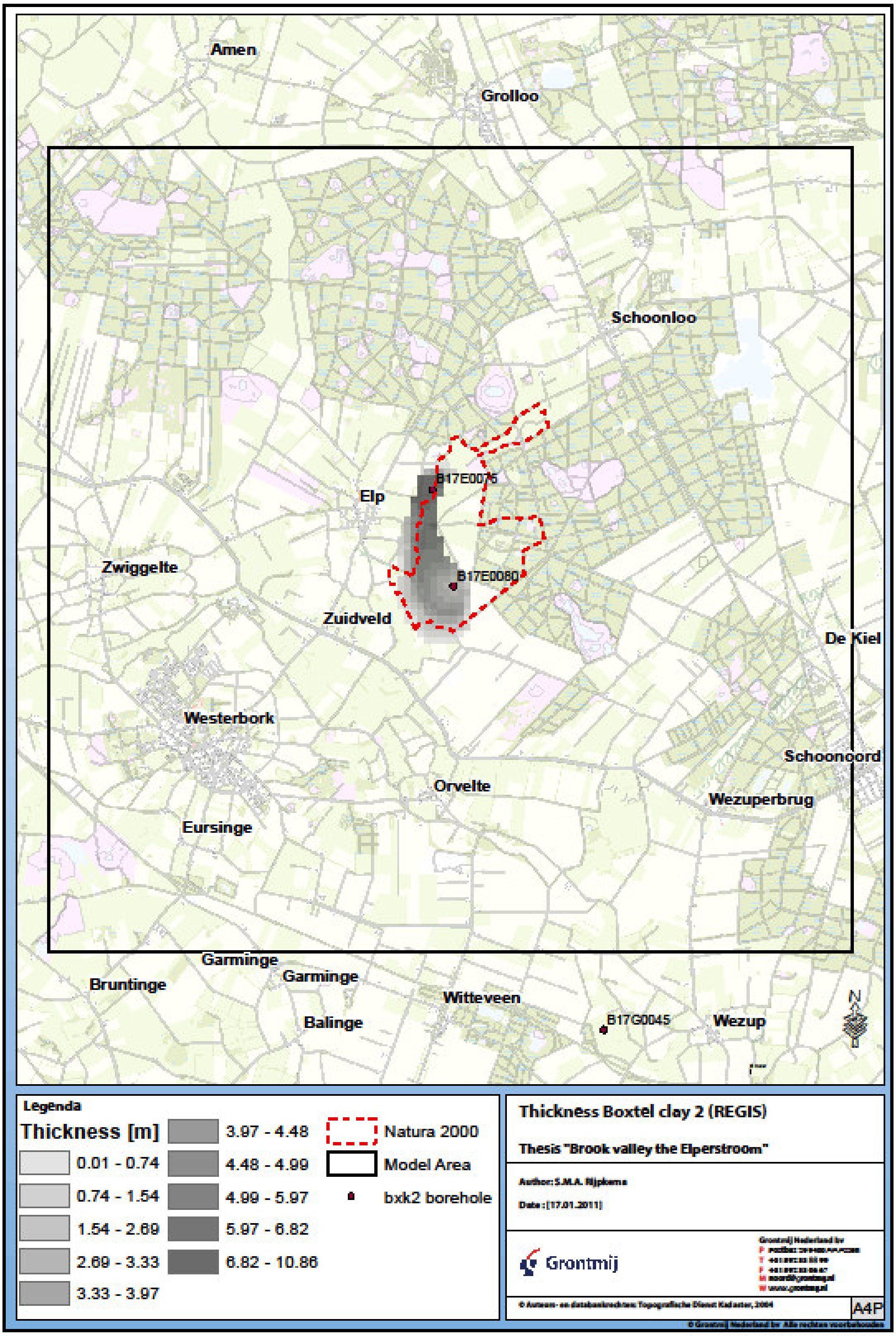
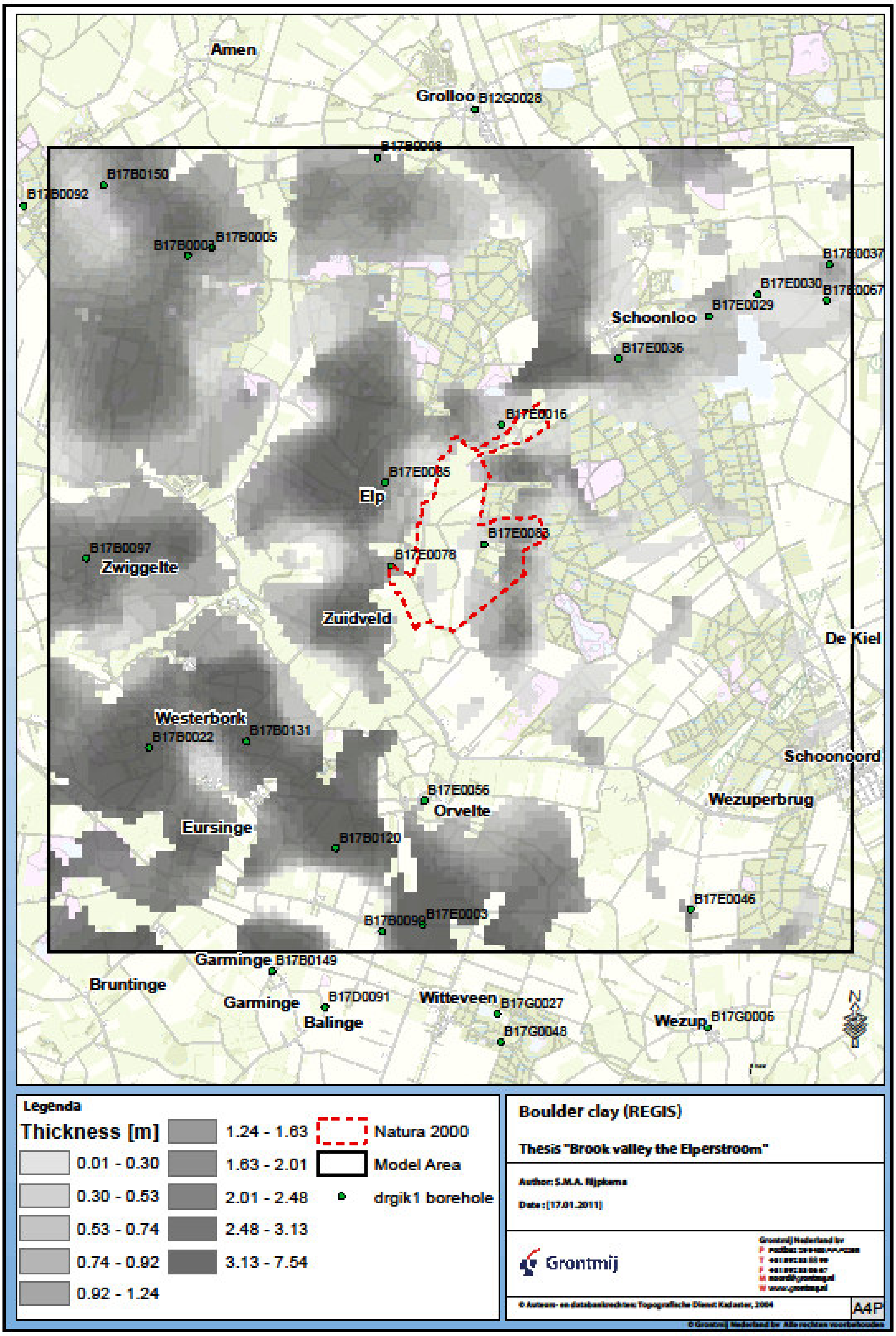
-1100
-1200
-1300
-1400



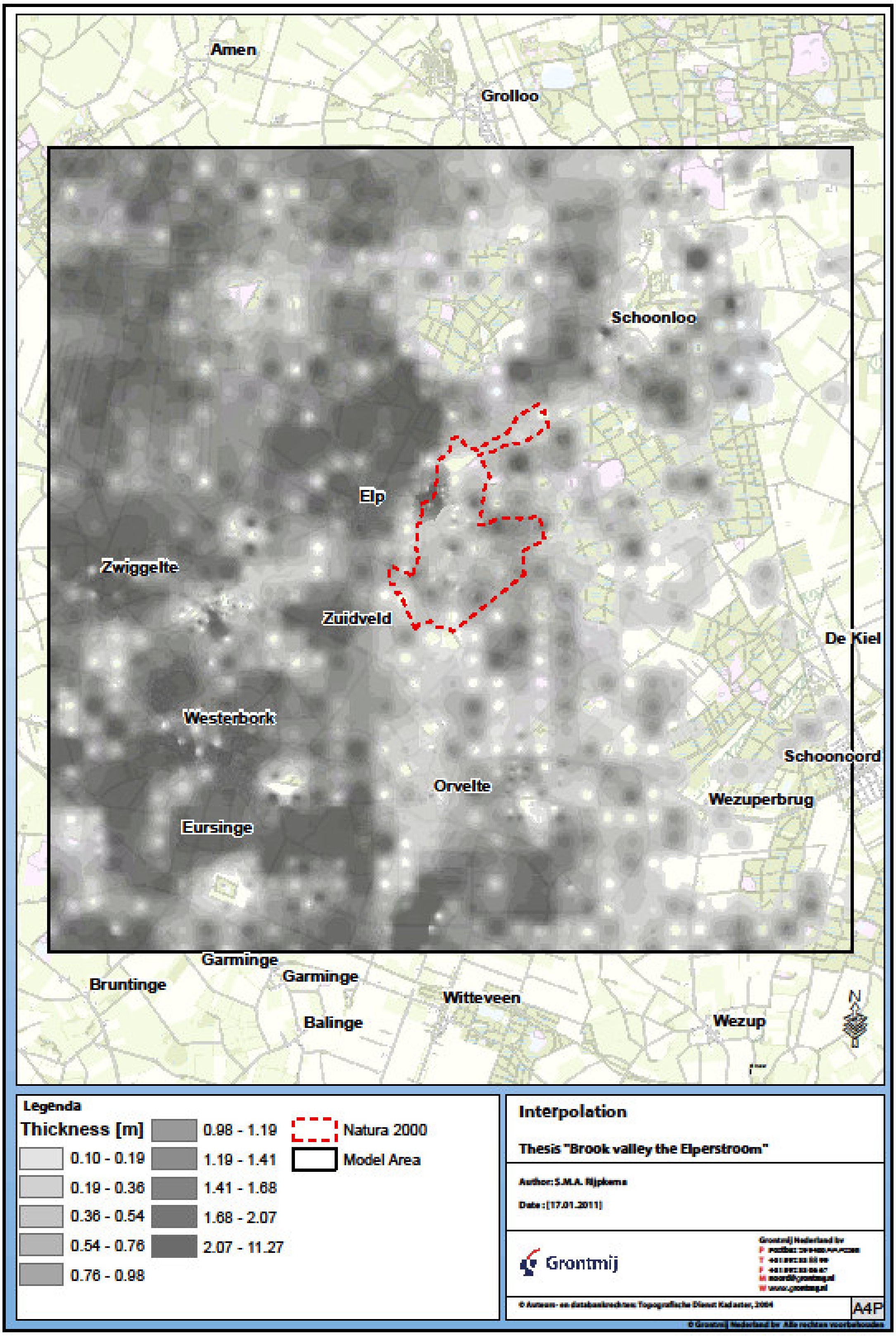
I 6 Thickness Boxtel clay 1



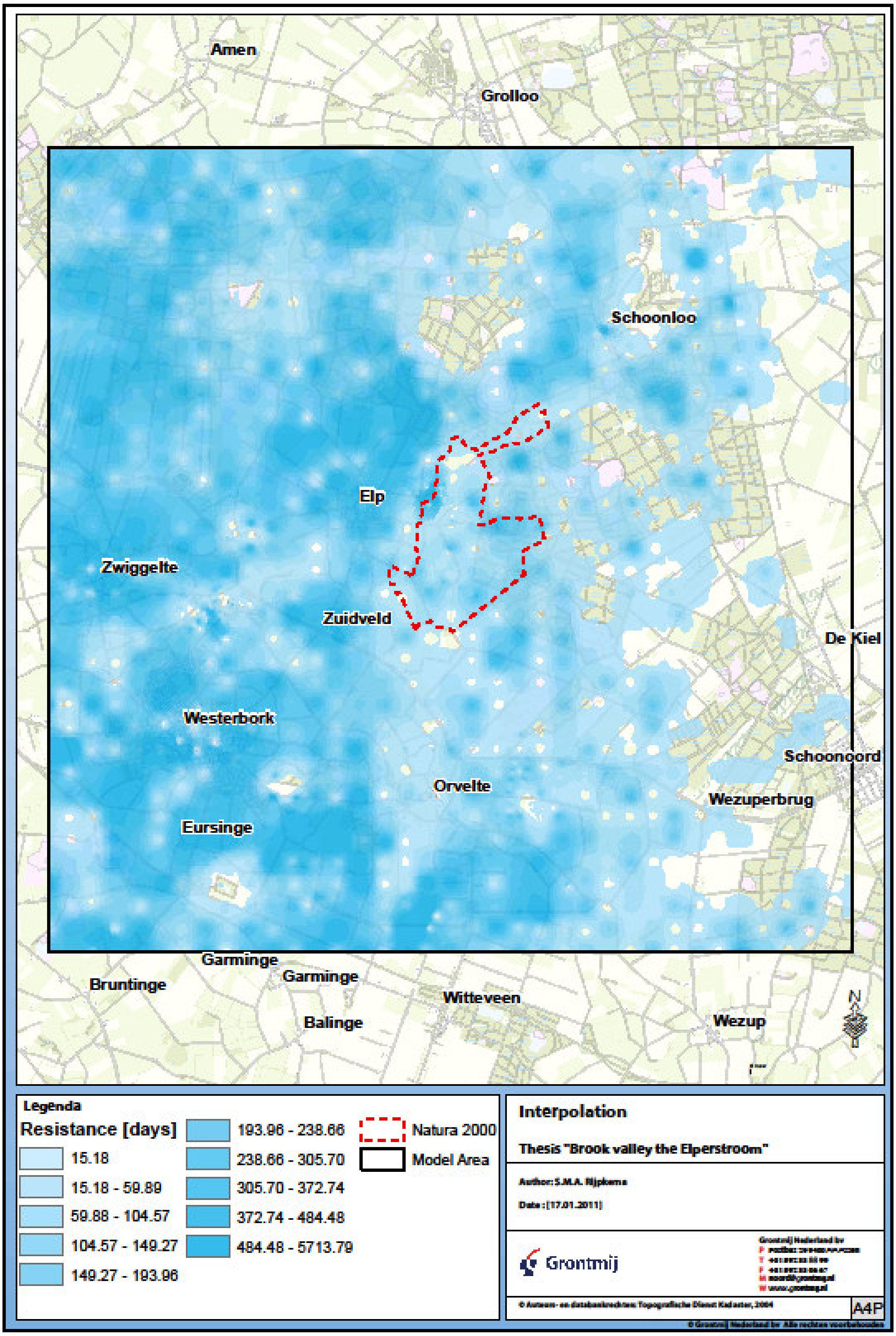
I 7 Thickness Boxtel clay 2



I 8 Thickness boulder clay



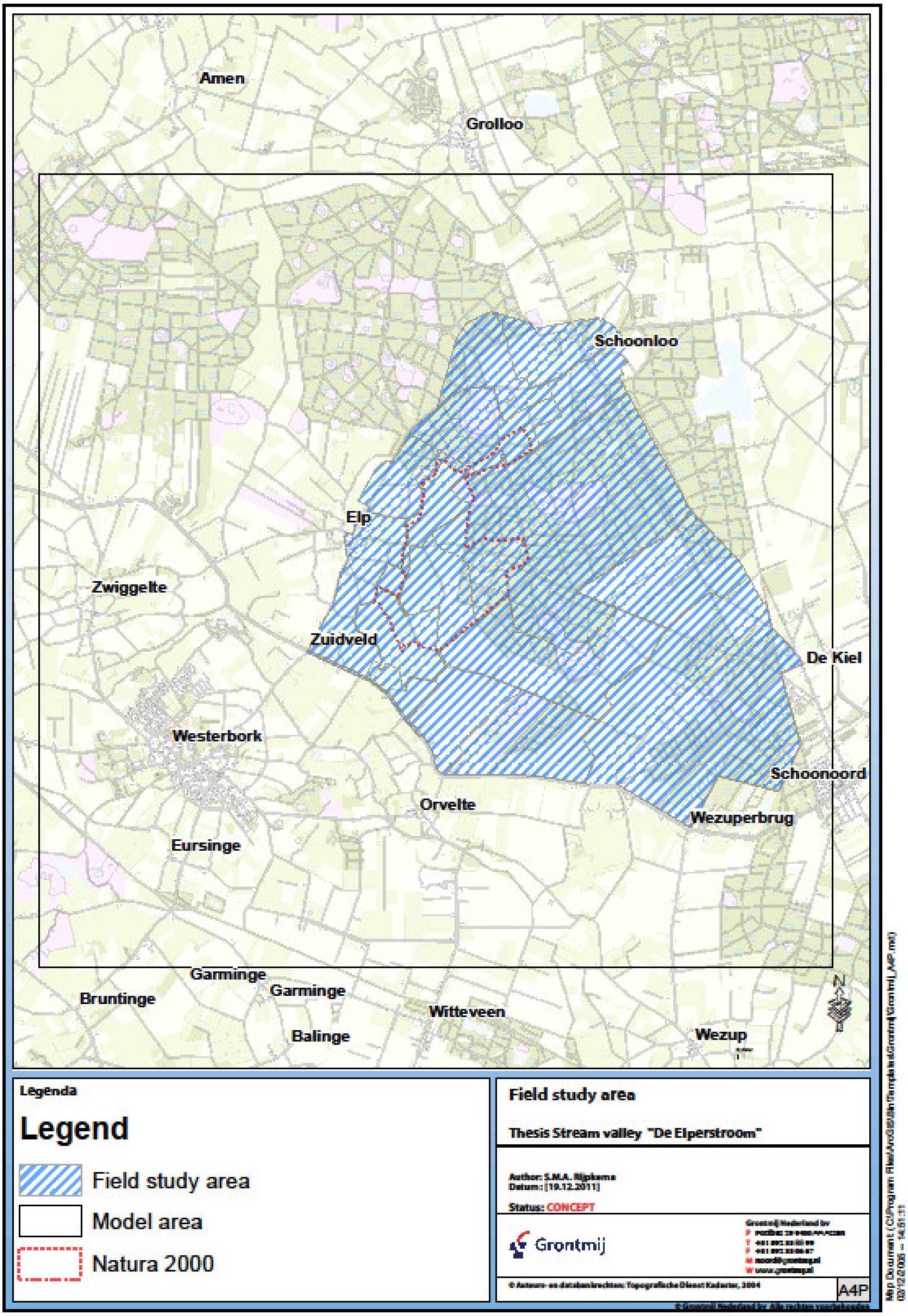
I 9 Thickness Interpolation



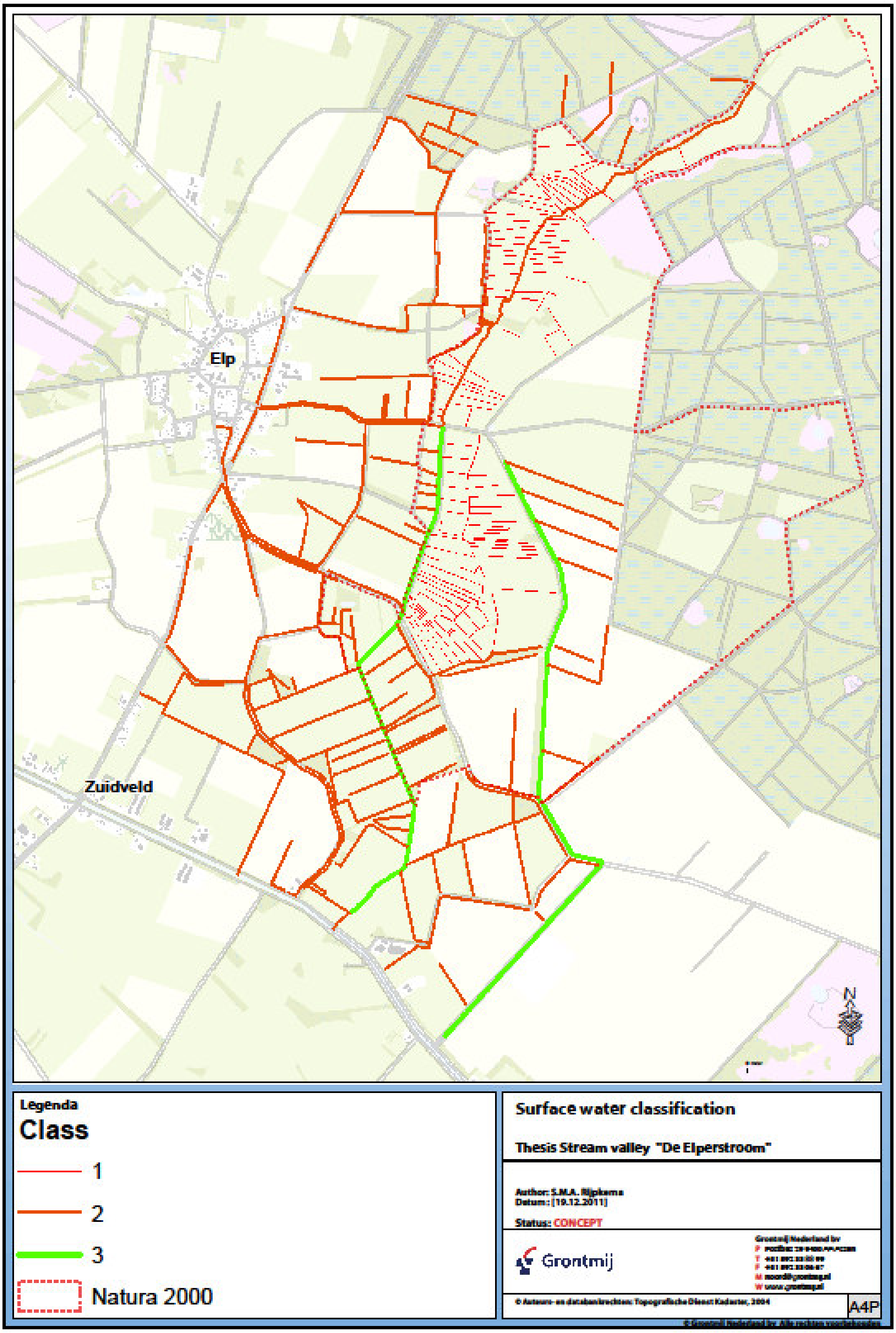
I 10 Resistance interplolation

Appendix II

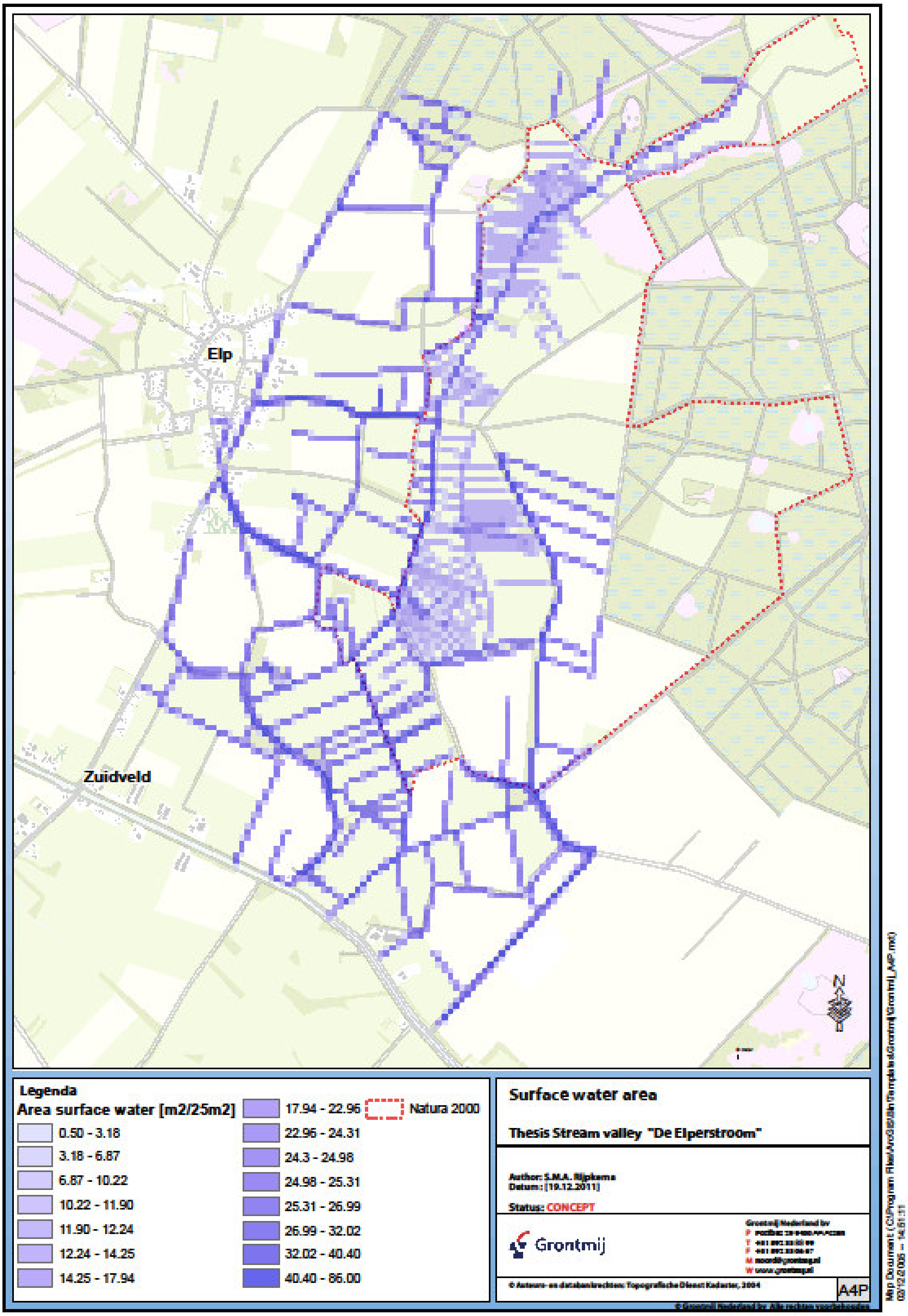
Field study surface water parameters



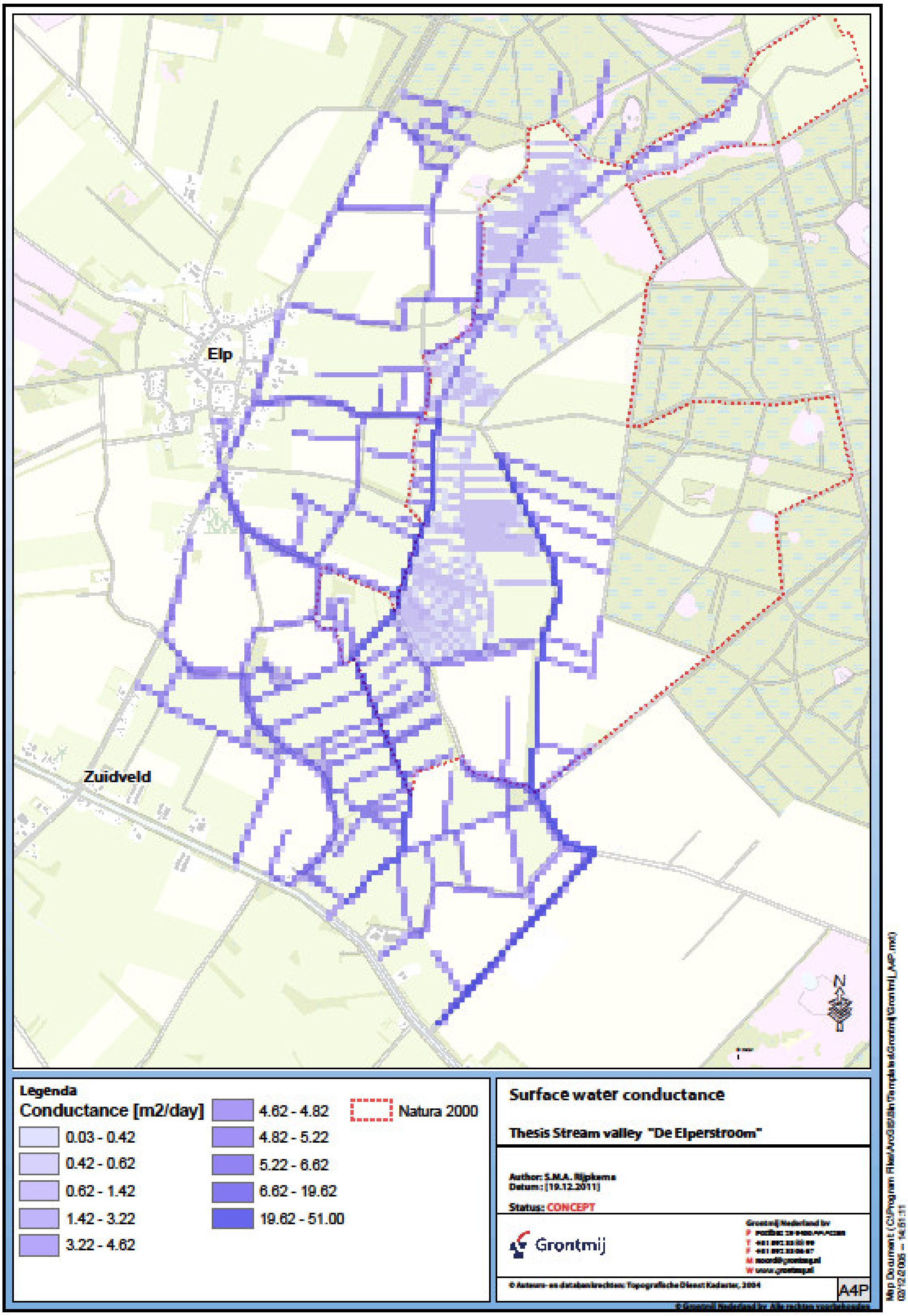
II 1 Field study area



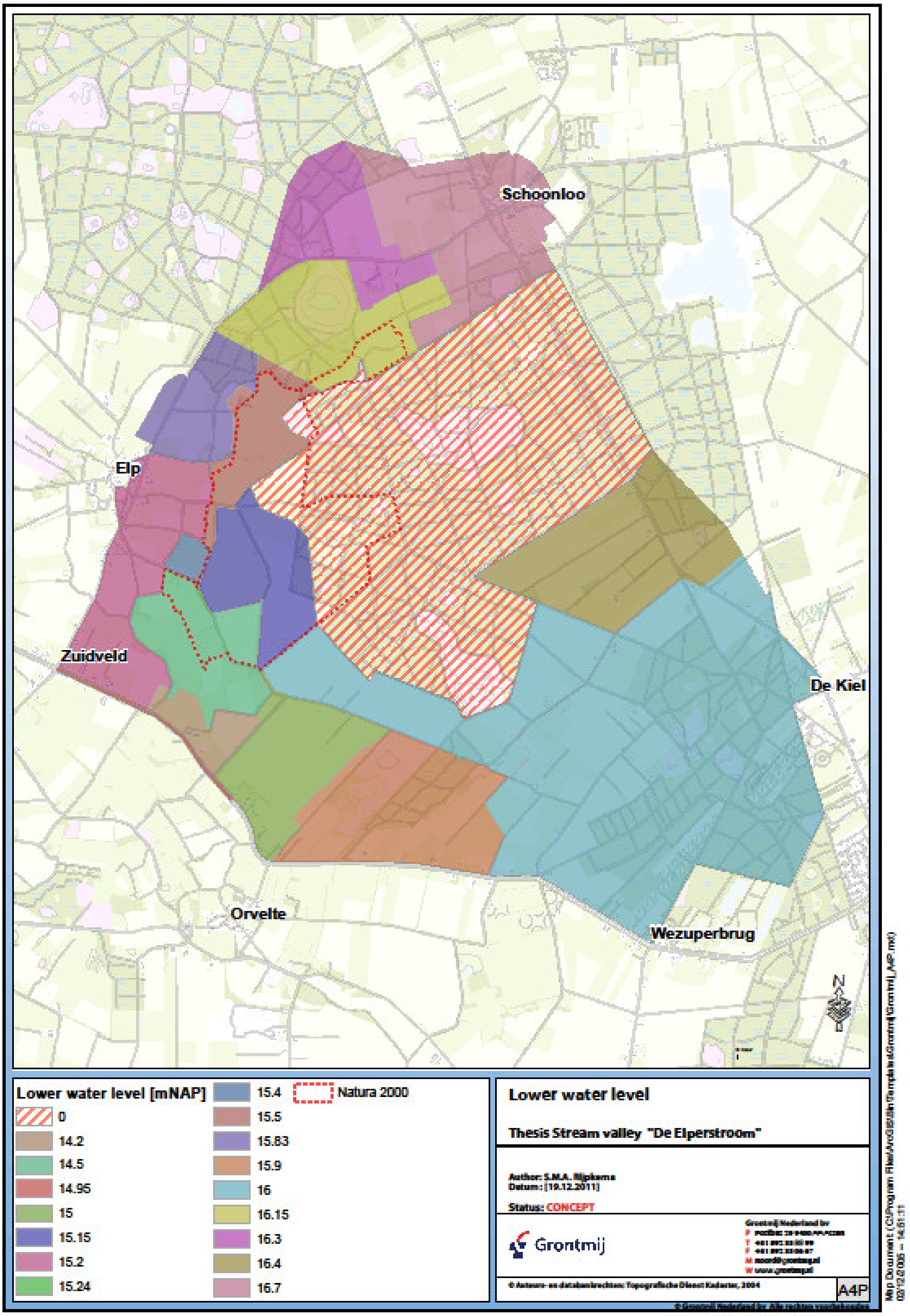
II 2 Classification waterways



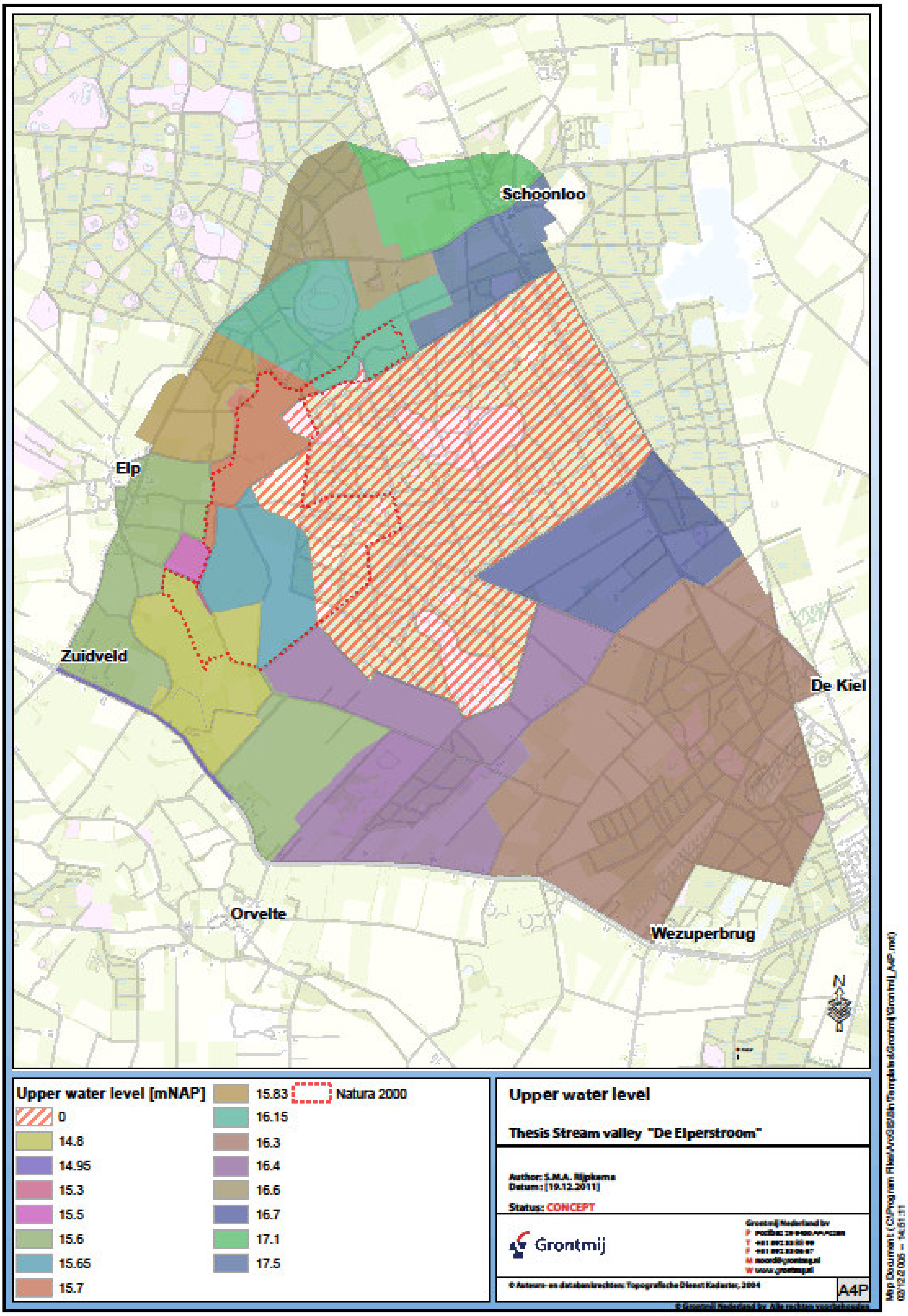
II 3 Area surface water



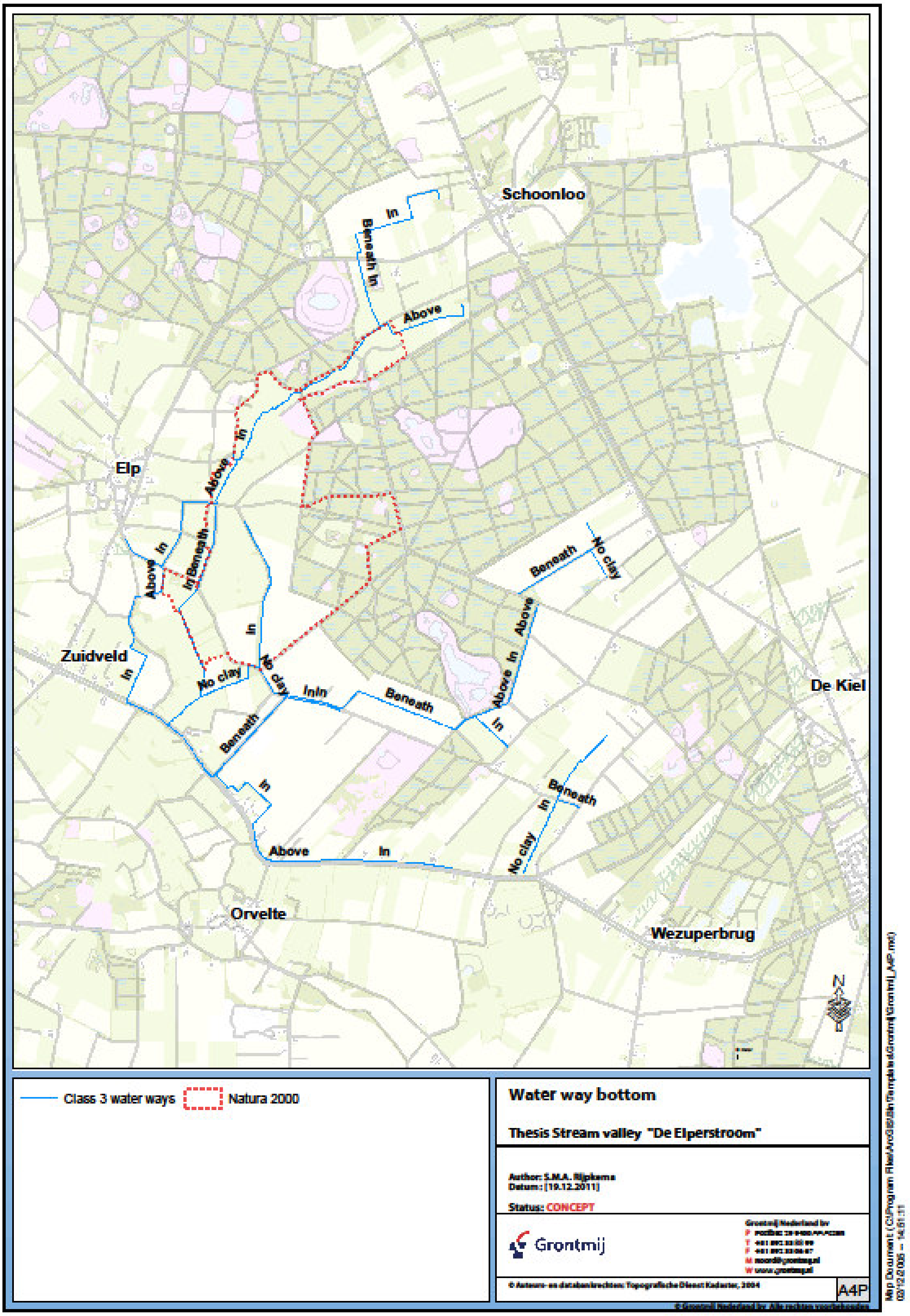
II 4 Surface water Conductance



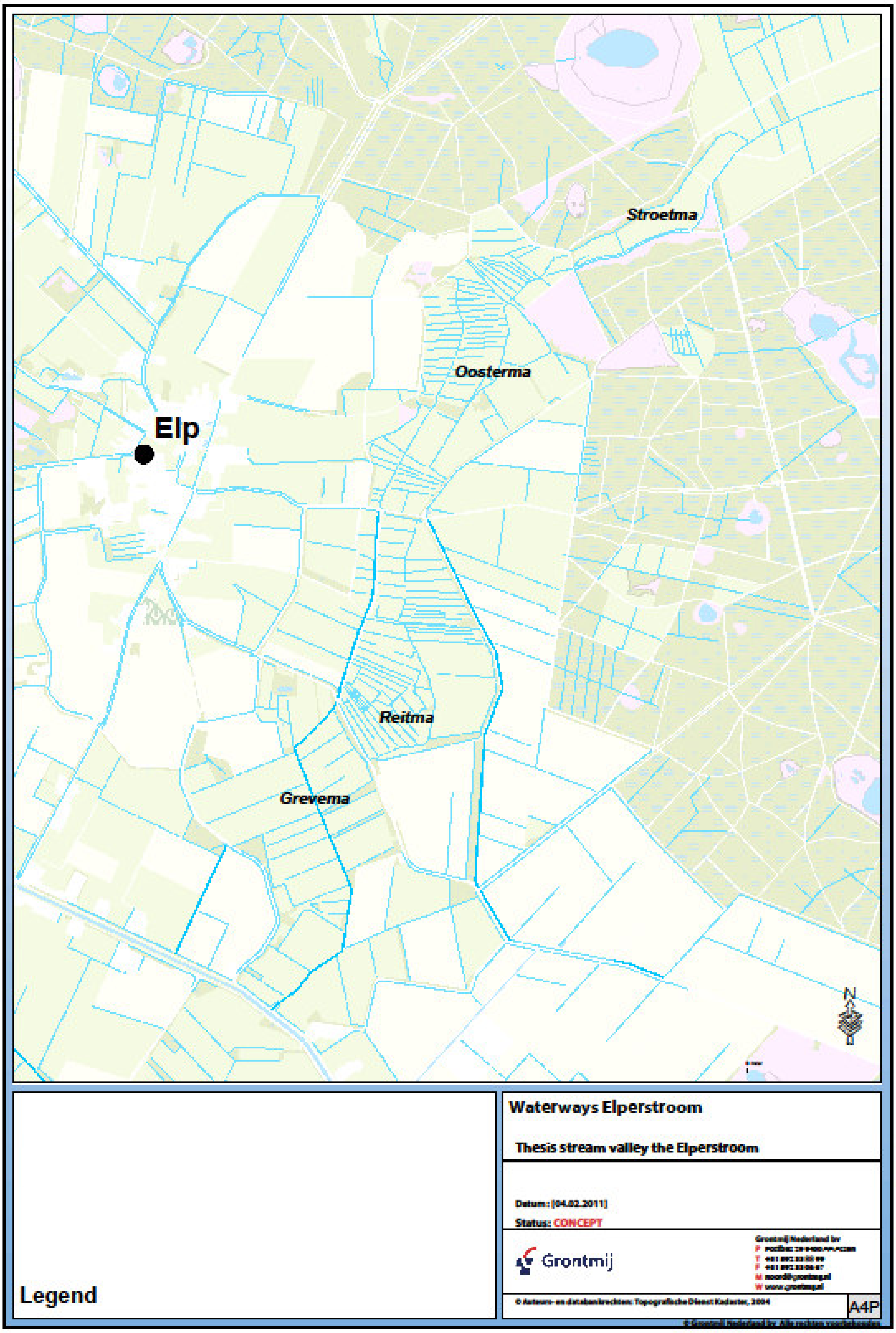
II 5 Lower water level



II 6 Upper water level



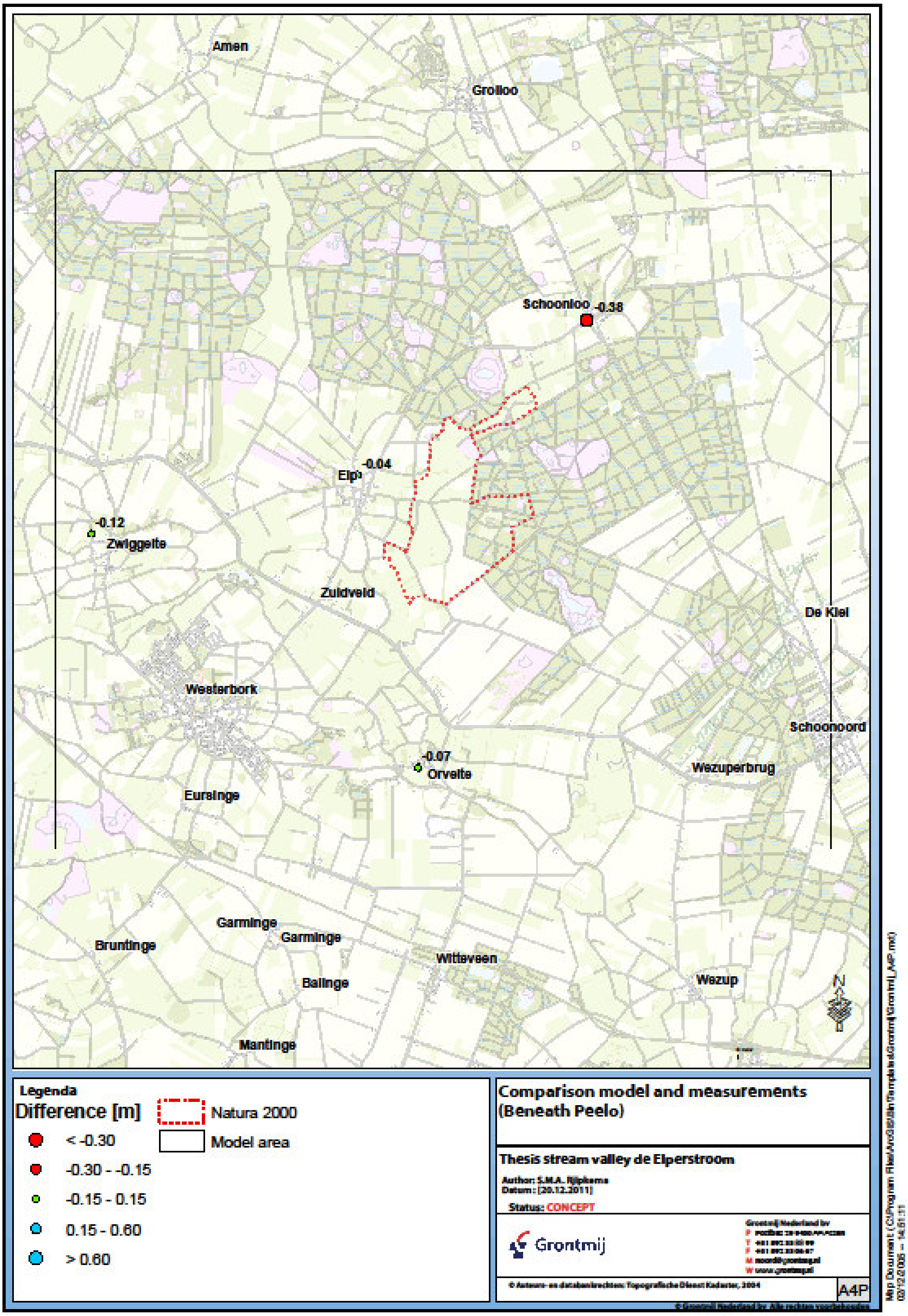
II 7 Bottom of the waterways with respect to the clay layer



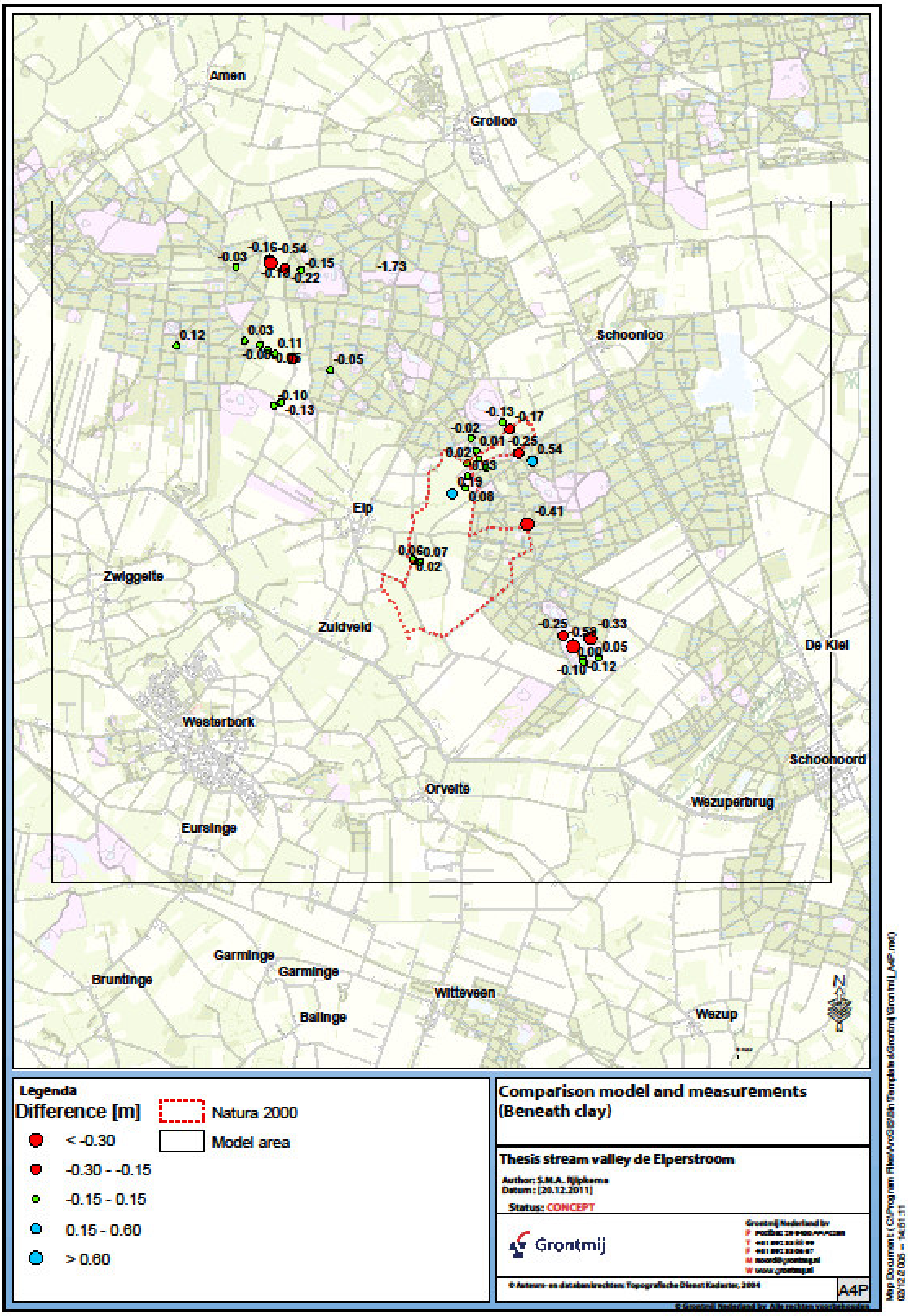
II 8 Waterways Elperstroom

Appendix III

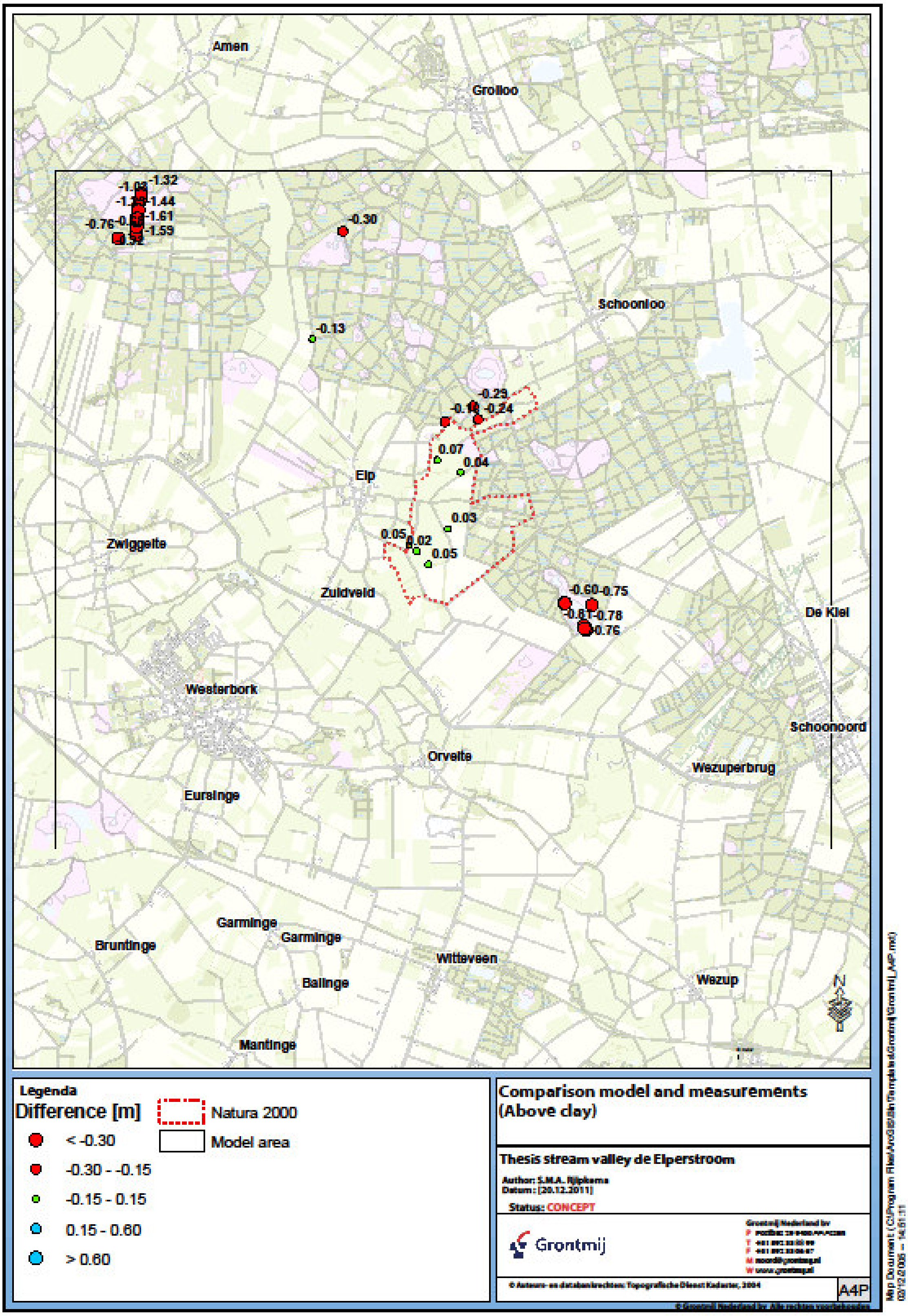
Calibration



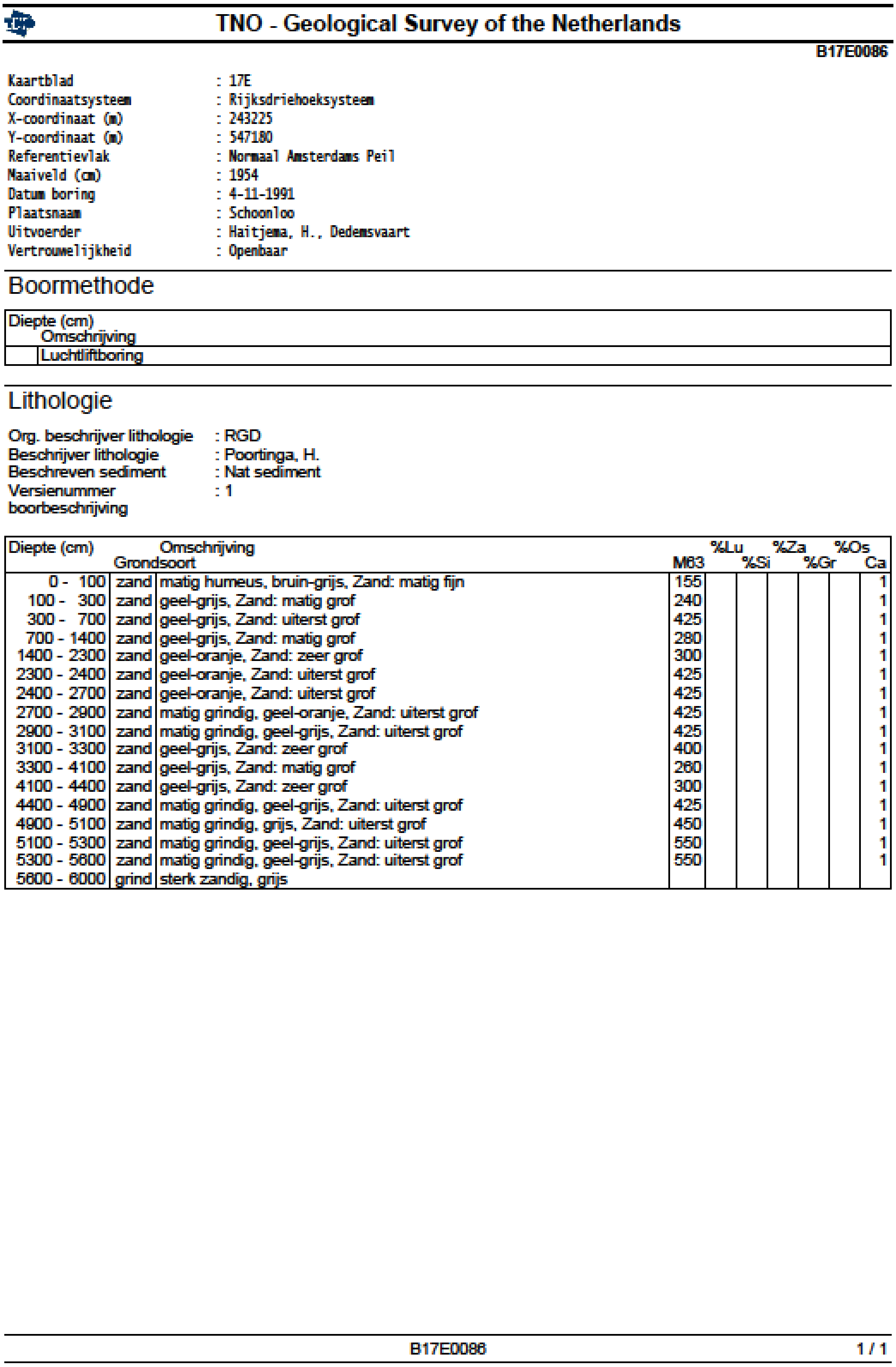
III 1 Comparison Peelo layer



III 2 Comparison beneath clay



III 3 Comparison above clay



TNO - Geological Survey of the Netherlands

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Y-coordinaat (m)	: 547180
Referentievlak	: Normaal Amsterdams Peil
Maaiveld (cm)	: 1954
Datum boring	: 4-11-1991
Plaatsnaam	: Schoonloo
Uitvoerder	: Haitjema, H., Dedemsvaart
Vertrouwelijkheid	: Openbaar

Boormethode

Diepte (cm)	Omschrijving
	Luchtliftboring

Lithologie

Org. beschrijver lithologie	: RGD
Beschrijver lithologie	: Poortinga, H.
Beschreven sediment	: Nat sediment
Versienummer boorbeschrijving	: 1

Diepte (cm)	Grondsoort	Omschrijving	M63	%Lu	%Si	%Za	%Gr	%Os	Ca
0 - 100	zand	matig humeus, bruin-grijs, Zand: matig fijn	155						1
100 - 300	zand	geel-grijs, Zand: matig grof	240						1
300 - 700	zand	geel-grijs, Zand: uiterst grof	425						1
700 - 1400	zand	geel-grijs, Zand: matig grof	280						1
1400 - 2300	zand	geel-oranje, Zand: zeer grof	300						1
2300 - 2400	zand	geel-oranje, Zand: uiterst grof	425						1
2400 - 2700	zand	geel-oranje, Zand: uiterst grof	425						1
2700 - 2900	zand	matig grindig, geel-oranje, Zand: uiterst grof	425						1
2900 - 3100	zand	matig grindig, geel-grijs, Zand: uiterst grof	425						1
3100 - 3300	zand	geel-grijs, Zand: zeer grof	400						1
3300 - 4100	zand	geel-grijs, Zand: matig grof	260						1
4100 - 4400	zand	geel-grijs, Zand: zeer grof	300						1
4400 - 4900	zand	matig grindig, geel-grijs, Zand: uiterst grof	425						1
4900 - 5100	zand	matig grindig, grijs, Zand: uiterst grof	450						1
5100 - 5300	zand	matig grindig, geel-grijs, Zand: uiterst grof	550						1
5300 - 5600	zand	matig grindig, geel-grijs, Zand: uiterst grof	550						1
5600 - 6000	grind	sterk zandig, grijs							

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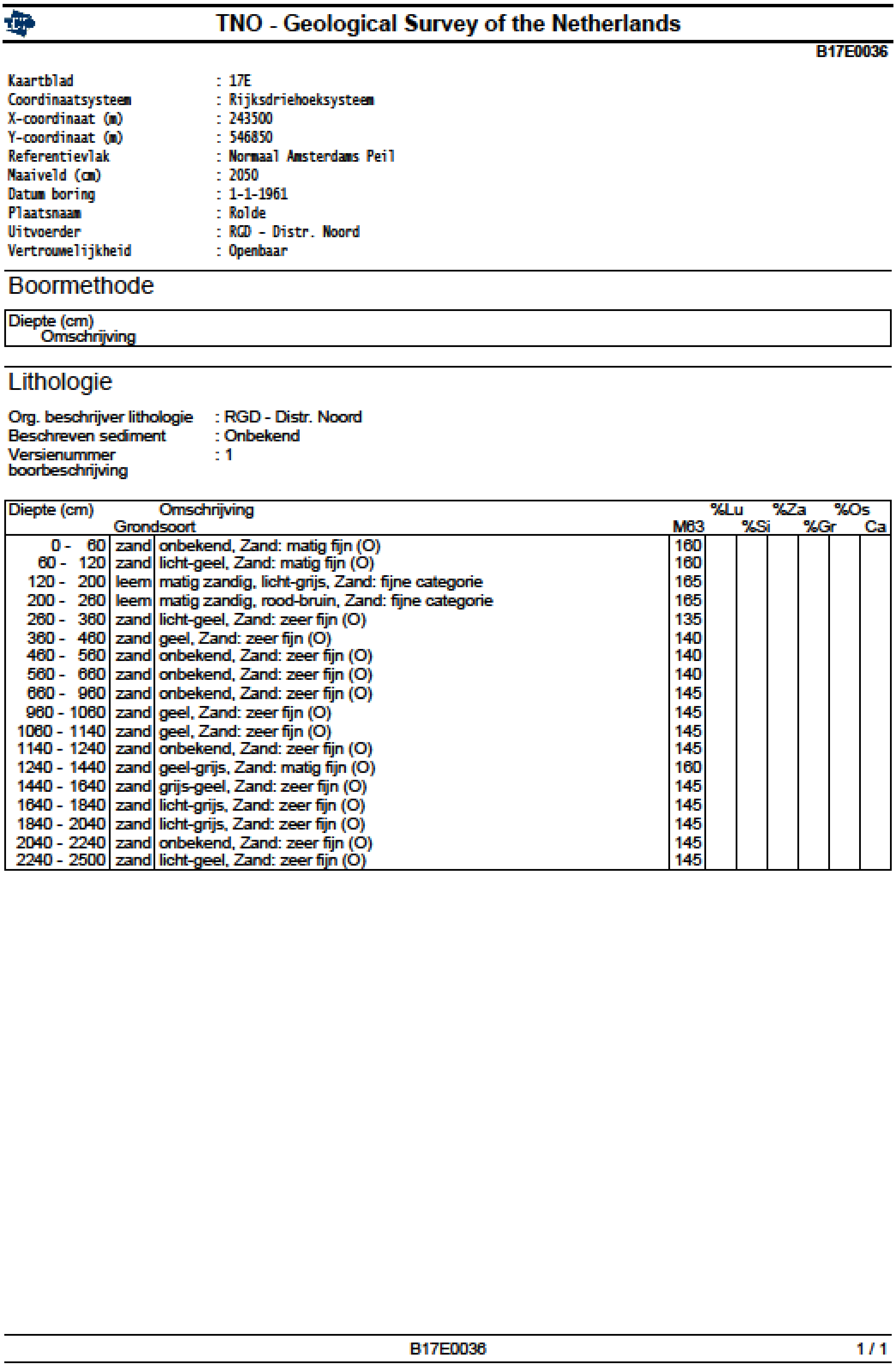
III 4 Borehole log B17E0086



TNO - Geological Survey of the Netherlands

B17E0036

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X-coordinaat (m)	: 243500
Y-coordinaat (m)	: 546850
Referentievlak	: Normaal Amsterdams Peil
Maaiveld (cm)	: 2050
Datum boring	: 1-1-1961
Plaatsnaam	: Rolde
Uitvoerder	: RGD - Distr. Noord
Vertrouwelijkheid	: Openbaar

Boormethode

Diepte (cm) Omschrijving

Lithologie

Org. beschrijver lithologie	: RGD - Distr. Noord
Beschreven sediment	: Onbekend
Versienummer boorbeschrijving	: 1

Diepte (cm)	Grondsoort	Omschrijving	M63	%Lu	%Si	%Za	%Gr	%Os	Ca
0 - 60	zand	onbekend, Zand: matig fijn (O)	160						
60 - 120	zand	licht-geel, Zand: matig fijn (O)	160						
120 - 200	leem	matig zandig, licht-grijs, Zand: fijne categorie	165						
200 - 260	leem	matig zandig, rood-bruin, Zand: fijne categorie	165						
260 - 360	zand	licht-geel, Zand: zeer fijn (O)	135						
360 - 460	zand	geel, Zand: zeer fijn (O)	140						
460 - 560	zand	onbekend, Zand: zeer fijn (O)	140						
560 - 660	zand	onbekend, Zand: zeer fijn (O)	140						
660 - 960	zand	onbekend, Zand: zeer fijn (O)	145						
960 - 1060	zand	geel, Zand: zeer fijn (O)	145						
1060 - 1140	zand	geel, Zand: zeer fijn (O)	145						
1140 - 1240	zand	onbekend, Zand: zeer fijn (O)	145						
1240 - 1440	zand	geel-grijs, Zand: matig fijn (O)	160						
1440 - 1640	zand	grijs-geel, Zand: zeer fijn (O)	145						
1640 - 1840	zand	licht-grijs, Zand: zeer fijn (O)	145						
1840 - 2040	zand	licht-grijs, Zand: zeer fijn (O)	145						
2040 - 2240	zand	onbekend, Zand: zeer fijn (O)	145						
2240 - 2500	zand	licht-geel, Zand: zeer fijn (O)	145						

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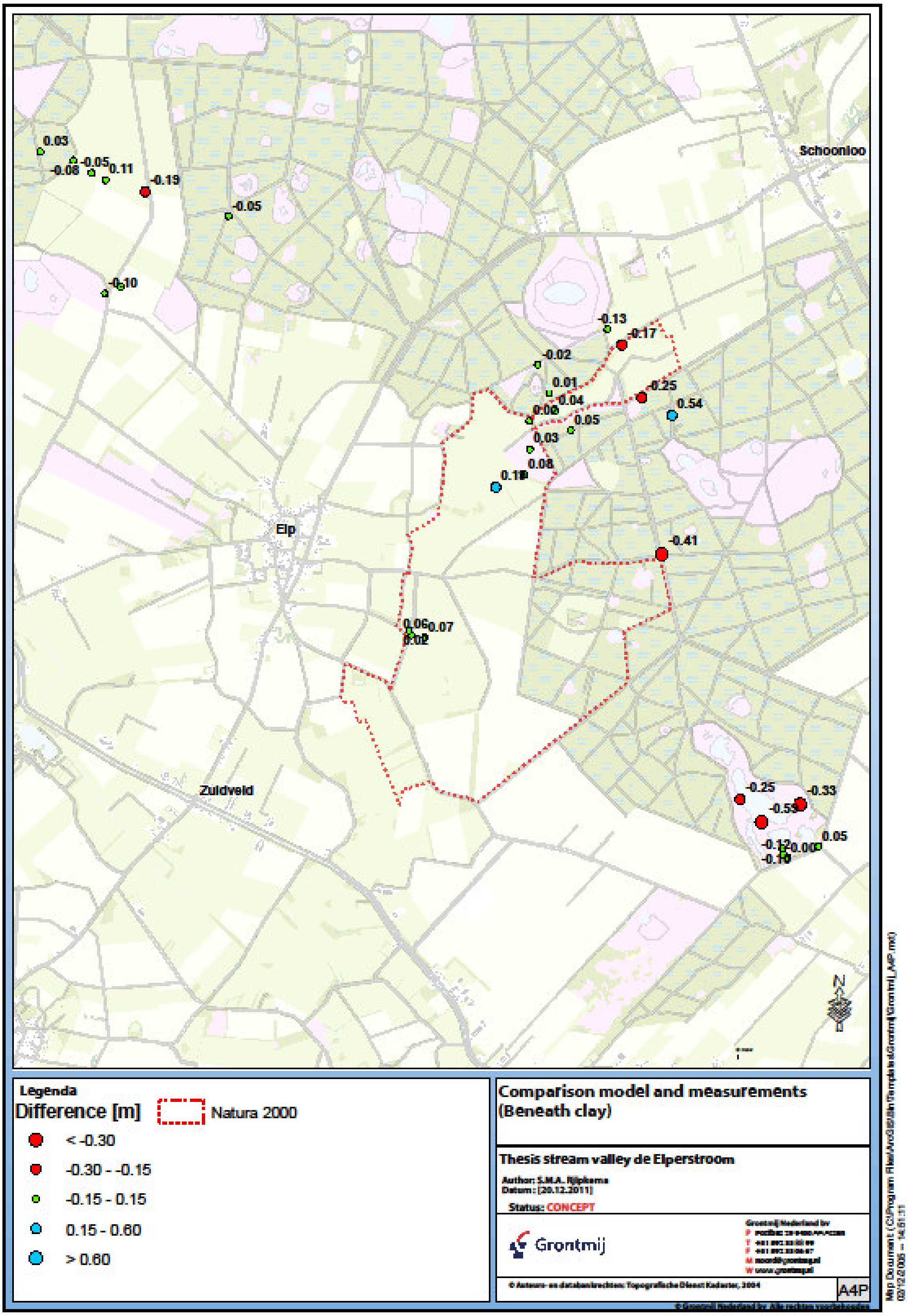
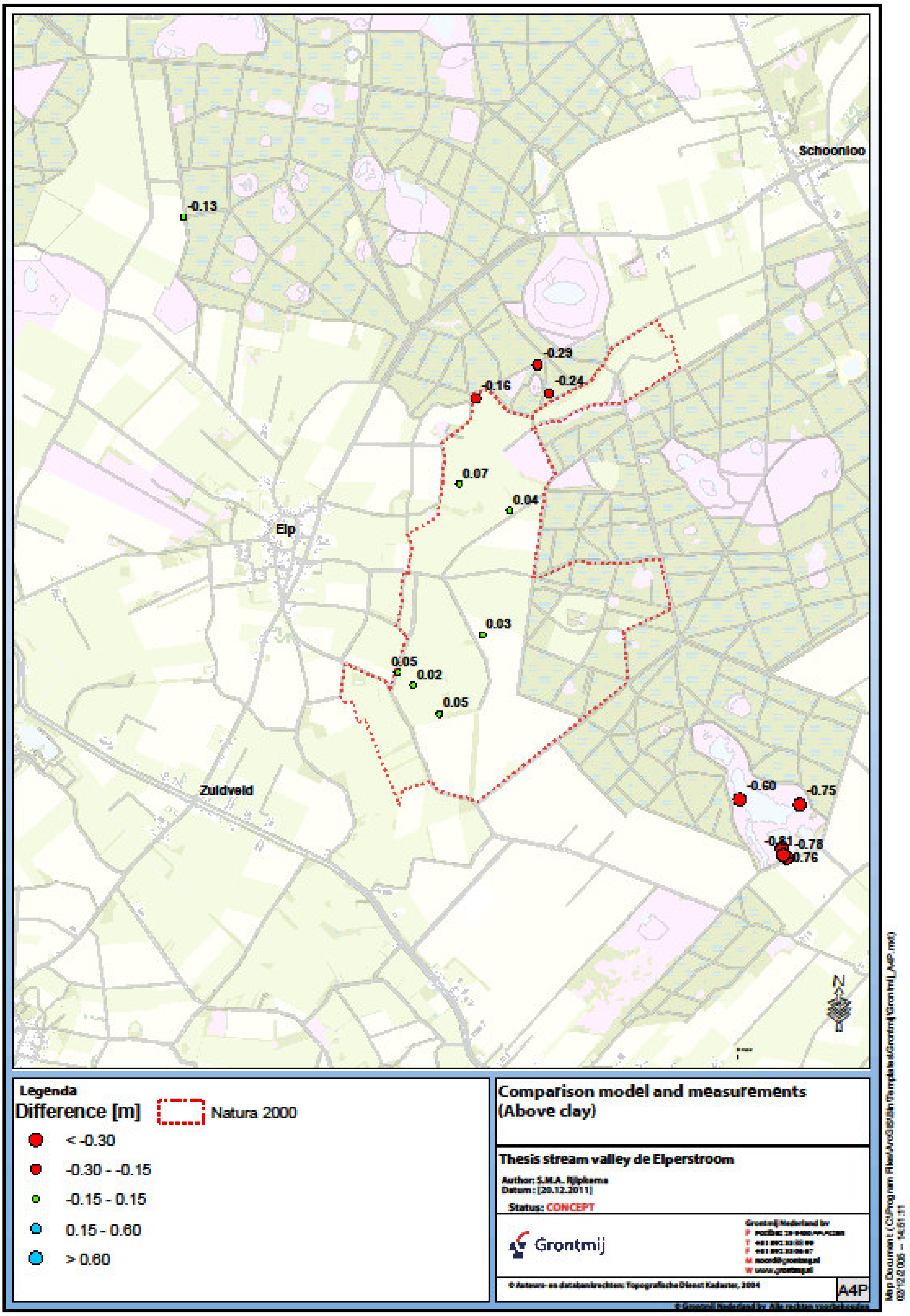
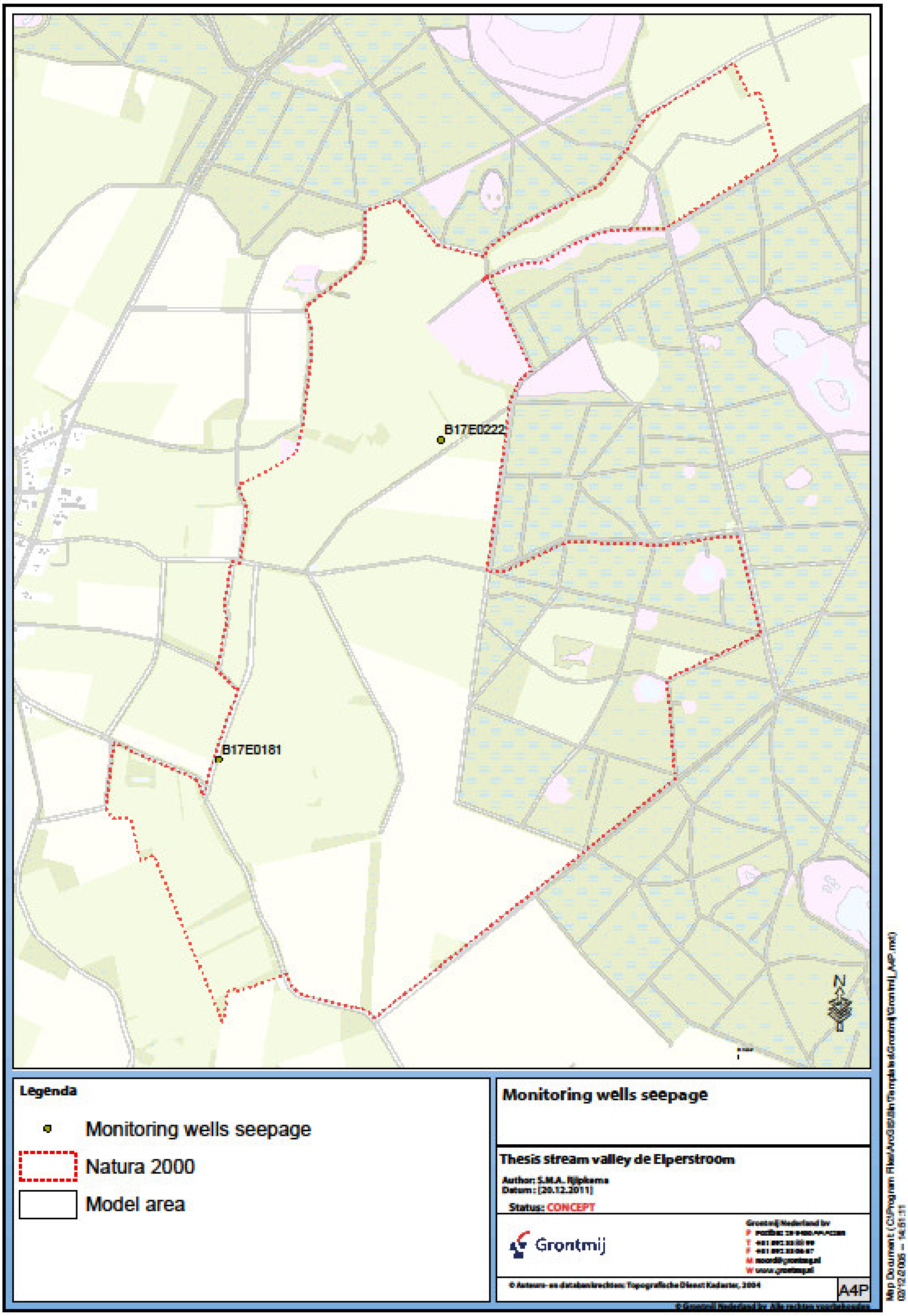
III 5 Borehole log B17E0036



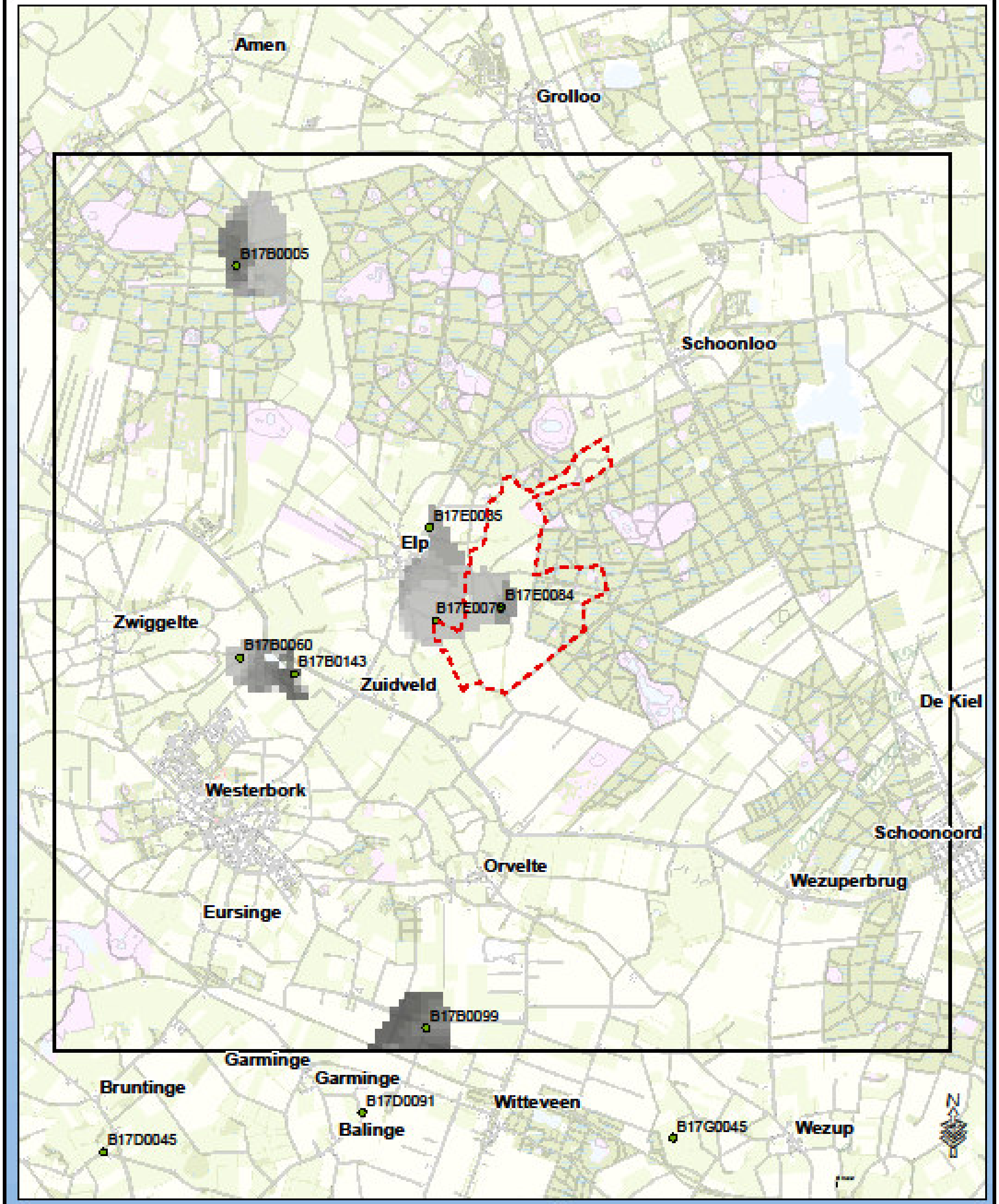
III 6 Comparison model measurements, zoom



Ill 7 Comparison model measurements, zoom



III 8 Monitorring Wells seepage



Legenda

Thickness [m]			
▨ 0.02 - 0.17	▨ 0.40 - 0.59	⬚ Natura 2000	
▨ 0.17 - 0.20	▨ 0.59 - 0.78	☐ Model Area	
▨ 0.20 - 0.27	▨ 0.78 - 0.94	● bxk1 borehole	
▨ 0.27 - 0.31	▨ 0.94 - 1.13		
▨ 0.31 - 0.40	▨ 1.13 - 1.48		

Thickness Boxtel clay 1 (REGIS)

Thesis "Brook valley the Elperstroom"

Author: S.M.A. Rijpkema

Date : [17.01.2011]

Grontmij

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P [illegible]
T [illegible]
F [illegible]
M [illegible]
W [illegible]

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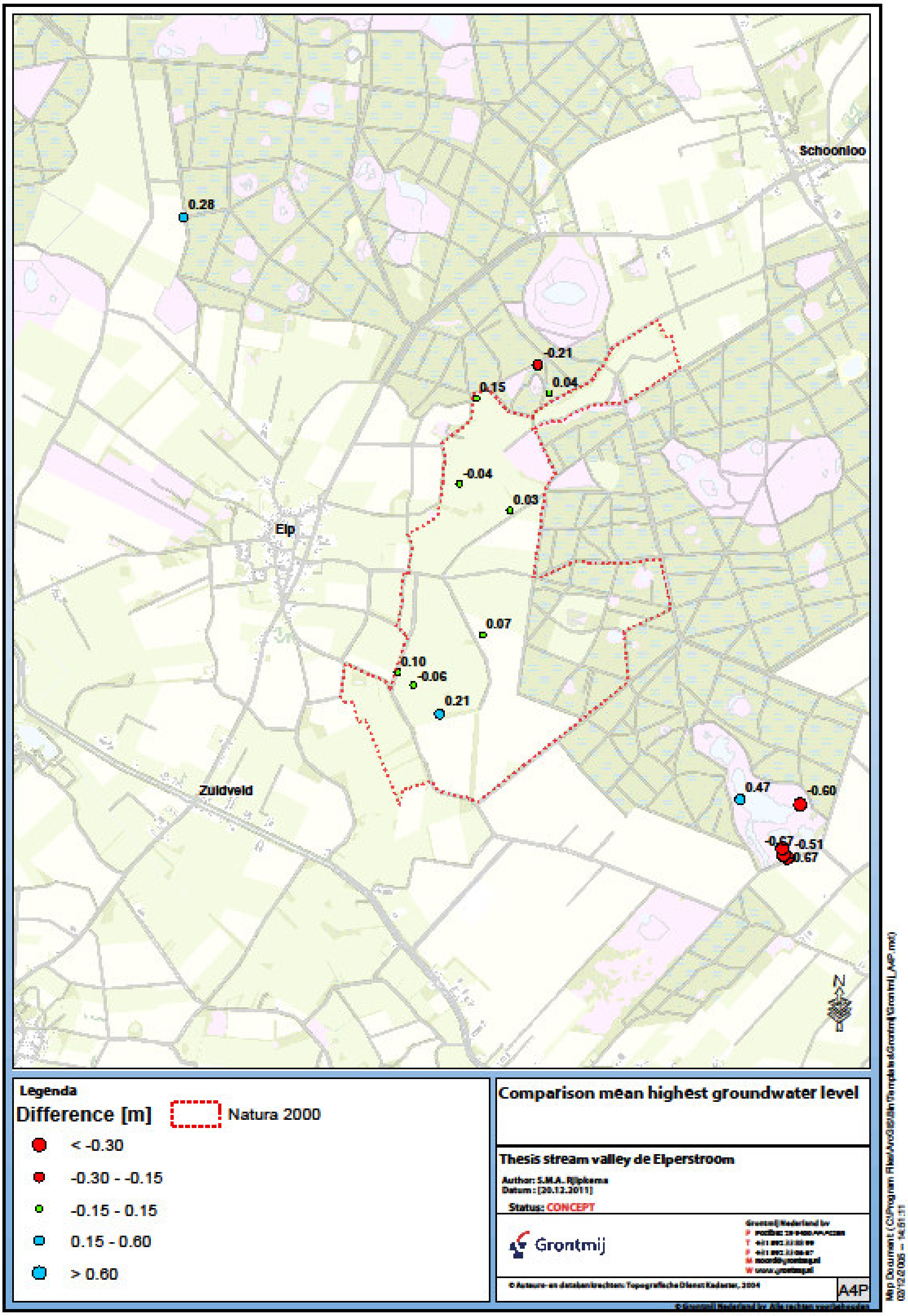
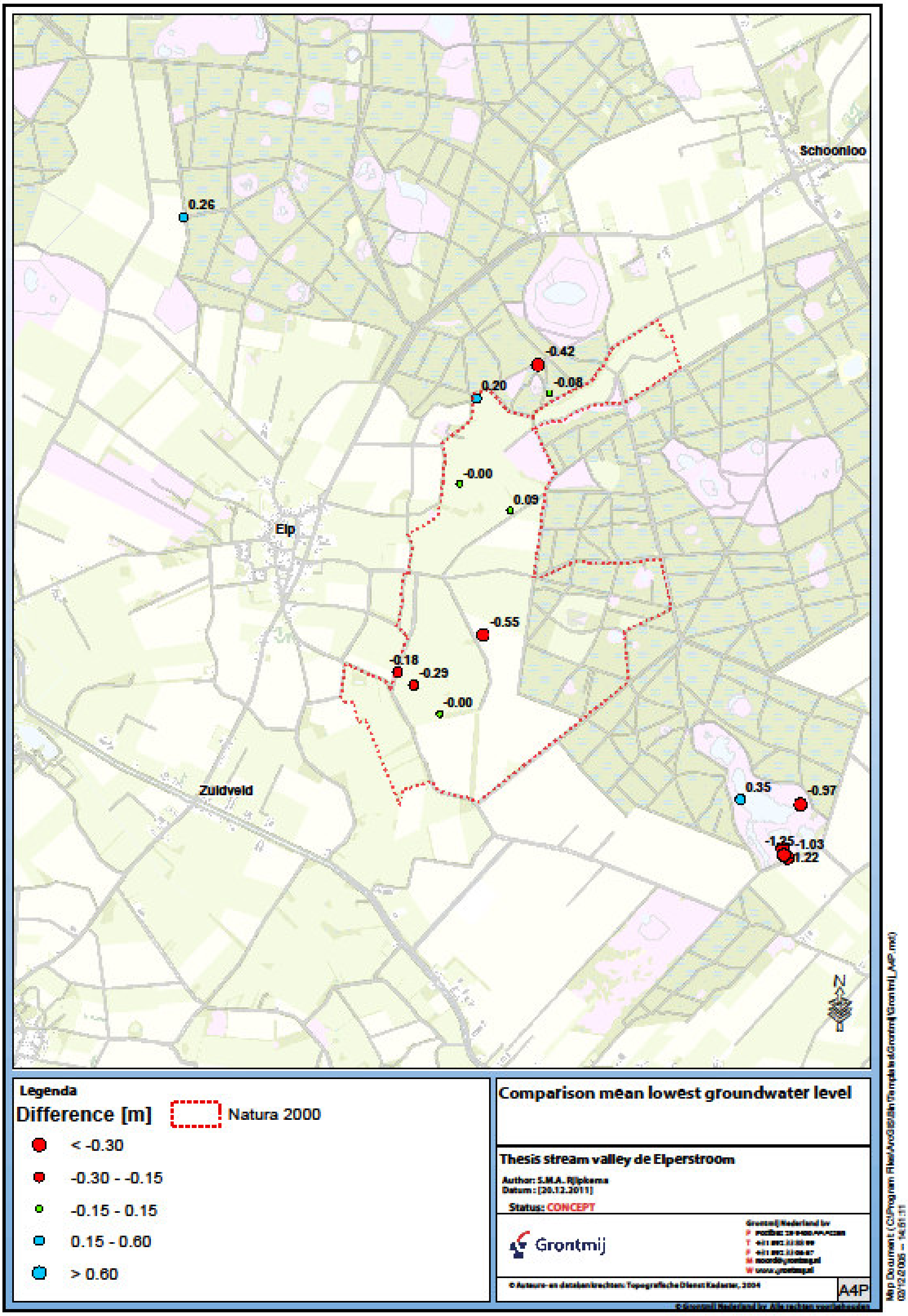


III 9 Comparison mean highest groundwater level



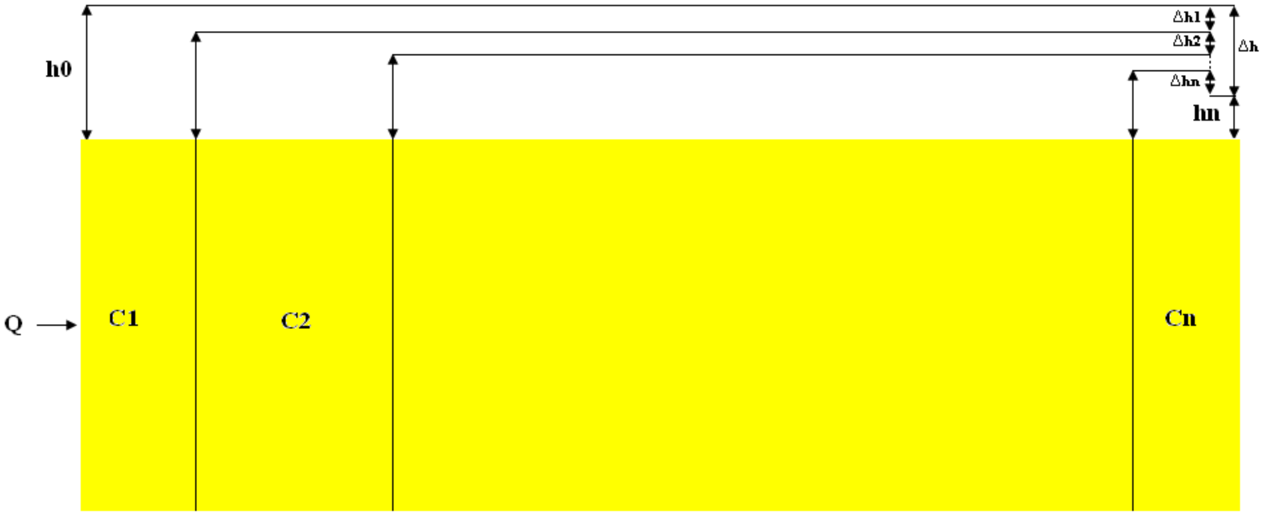
Ill 10 Comparison mean lowest groundwater level

Appendix IV

Upscaling

Equivalent hydraulic conductance

The equivalent hydraulic conductance for N stacked layers were the flow is perpendicular to the layers can be calculated as follows. The situation is given in the Figure below;



IV 1 Flow perpendicular to stacked layers with different conductance

The law of Darcy gives;

$$Q = C^{equi} \Delta h$$

Equation 36

Were C^{equi} is the equivalent conductance. The total drop of head, Δh equal to the drop of head of the individual layers;

$$\Delta h = \sum_{i=1}^{n} \Delta h_i$$

Equation 37

Wereas the volumetric flux through all the layers is constant, Darcy's equation for a single layer looks as follows;

$$Q = C_i \Delta h_i \Rightarrow \Delta h = \frac{Q}{C_i}$$

Equation 38

Combining this with equation 34 gives;

$$\Delta h = Q \sum_{i=1}^{n} \frac{1}{C_i} \Rightarrow \frac{\Delta h}{Q} = \sum_{i=1}^{n} \frac{1}{C_i}$$

Equation 39

Making use of equation 33 an equation for determining the equivalent conductance is found;

$$\frac{1}{C^{equi}} = \sum_{i=1}^{n} \frac{1}{C_i}$$

Equation 40

Surface water conductance

The equivalent conductance of a grid cell, with three classes of waterways is calculated in the following way. We start with the volumetric flux from/to the surface water, equation 24;

$$q^{m}_{river\,i,j,k} = SA_{i,j,k}\frac{h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}}{R_{i,j,k}} = C^{riv}_{i,j,k}\left(h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}\right)$$

Equation 24

In reality the flux consist out of three separate fluxes, one for each surface water class, so;

$$q^{m}_{river\,i,j,k} = q^{m}_{1\;i,j,k} + q^{m}_{2\;i,j,k} + q^{m}_{3\;i,j,k}$$

Equation 41

Filling in equation 24 again gives;

$$C^{riv}_{i,j,k}\left(h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}\right) = C^{1}_{i,j,k}\left(h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}\right) + C^{2}_{i,j,k}\left(h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}\right) + C^{3}_{i,j,k}\left(h^{m}_{river\,i,j,k} - h^{m}_{i,j,k}\right)$$

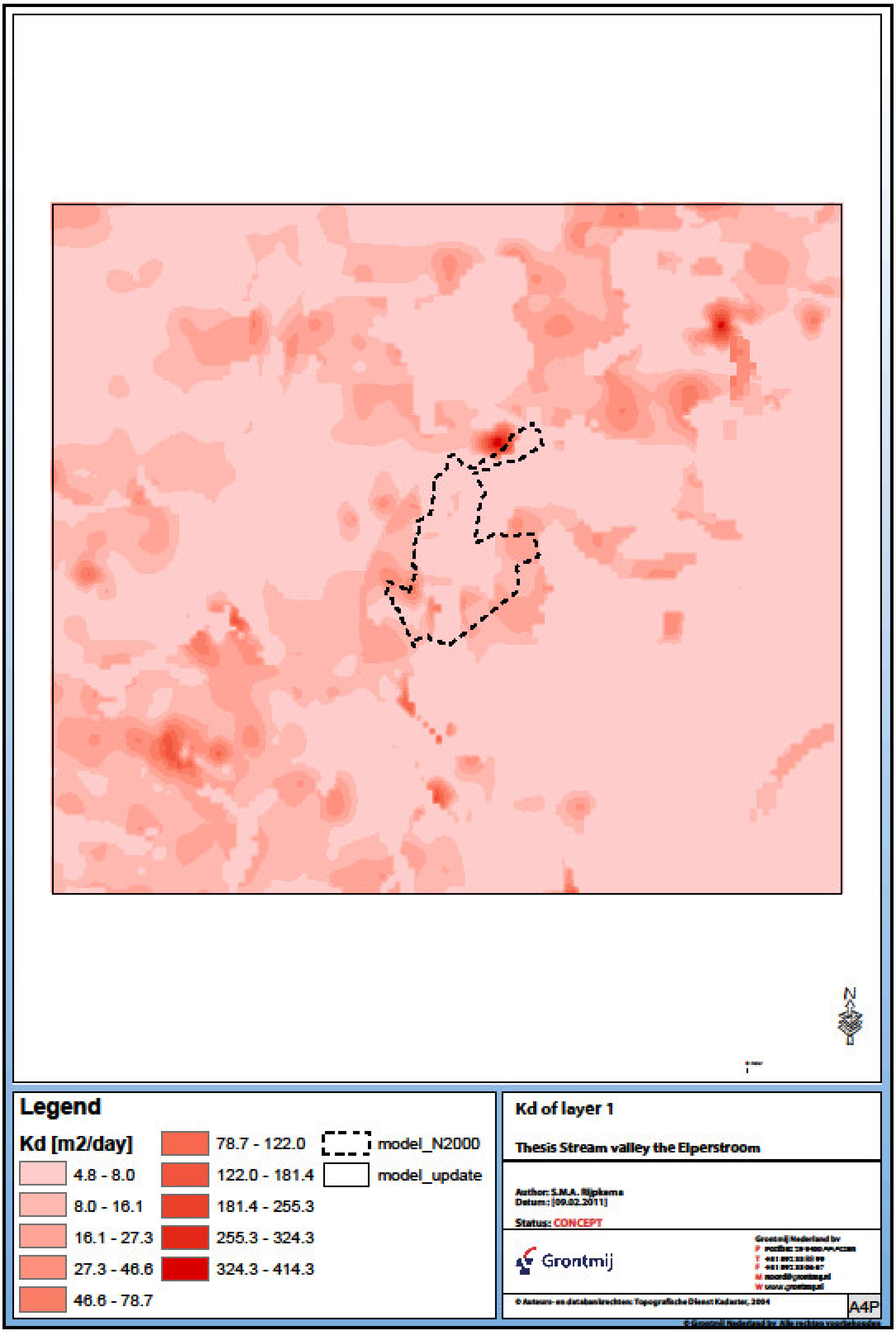
$$C^{riv}_{i,j,k} = C^{1}_{i,j,k} + C^{2}_{i,j,k} + C^{3}_{i,j,k} = \frac{SA^{1}_{i,j,k}}{R^{1}_{i,j,k}} + \frac{SA^{2}_{i,j,k}}{R^{2}_{i,j,k}} + \frac{SA^{3}_{i,j,k}}{R^{3}_{i,j,k}}$$

Equation 42

Were $SA^{1}_{i,j,k}, SA^{2}_{i,j,k}, SA^{3}_{i,j,k}$ are the surface water areas per class and $R^{1}_{i,j,k}, R^{2}_{i,j,k}, R^{3}_{i,j,k}$ are the resistances of the different classes.

Appendix V

MIPWA Subsurface parameters


Legend
Kd [m2/day]
4.8 - 8.0
8.0 - 16.1
16.1 - 27.3
27.3 - 46.6
46.6 - 78.7
78.7 - 122.0
122.0 - 181.4
181.4 - 255.3
255.3 - 324.3
324.3 - 414.3
model_N2000
model_update
N
Kd of layer 1
Thesis Stream valley the Elperstroom
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Datum: [09.02.2011]
Status: CONCEPT
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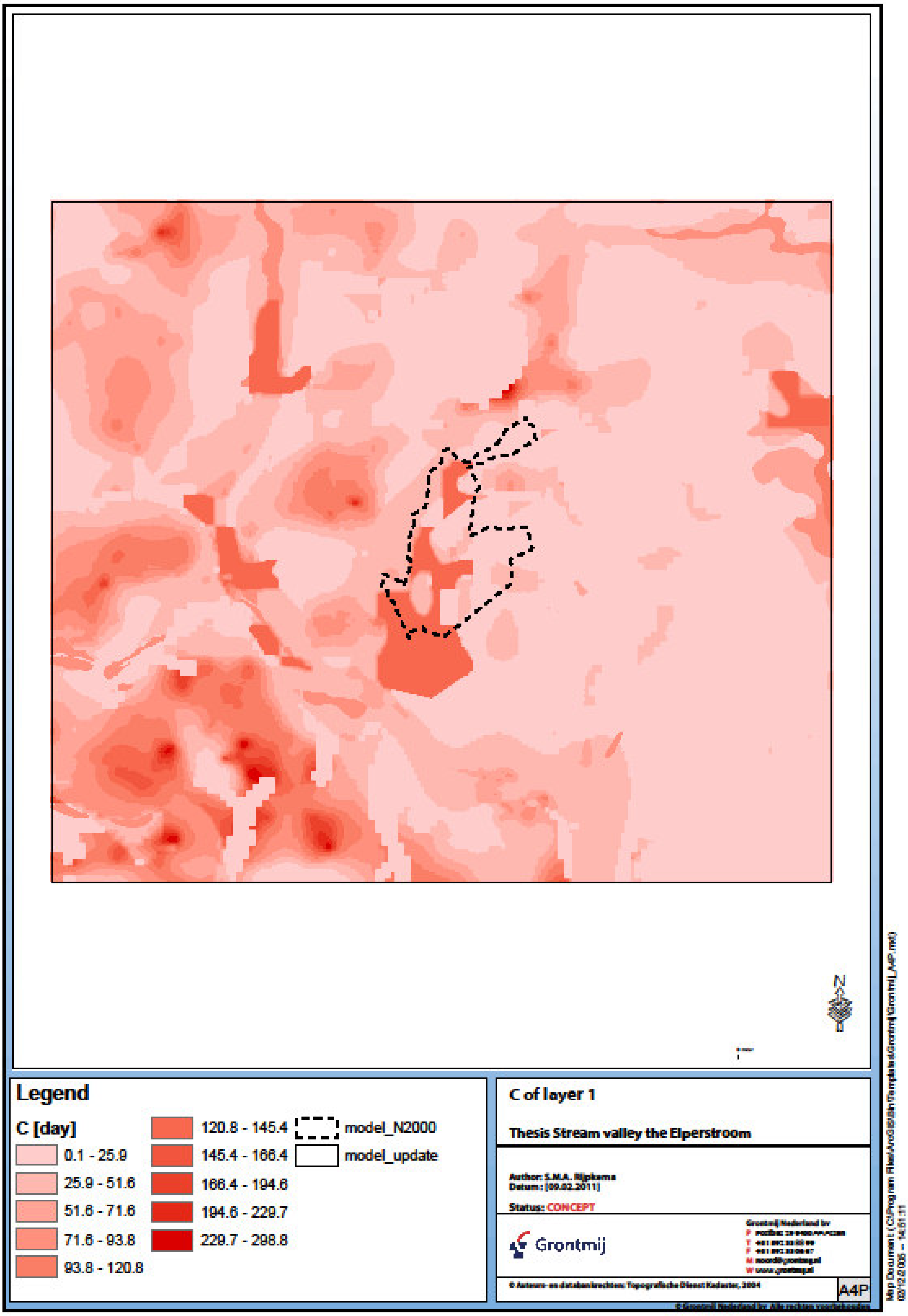
Legend
C [day]
0.1 - 25.9
25.9 - 51.6
51.6 - 71.6
71.6 - 93.8
93.8 - 120.8
120.8 - 145.4
145.4 - 166.4
166.4 - 194.6
194.6 - 229.7
229.7 - 298.8
model_N2000
model_update
N
C of layer 1
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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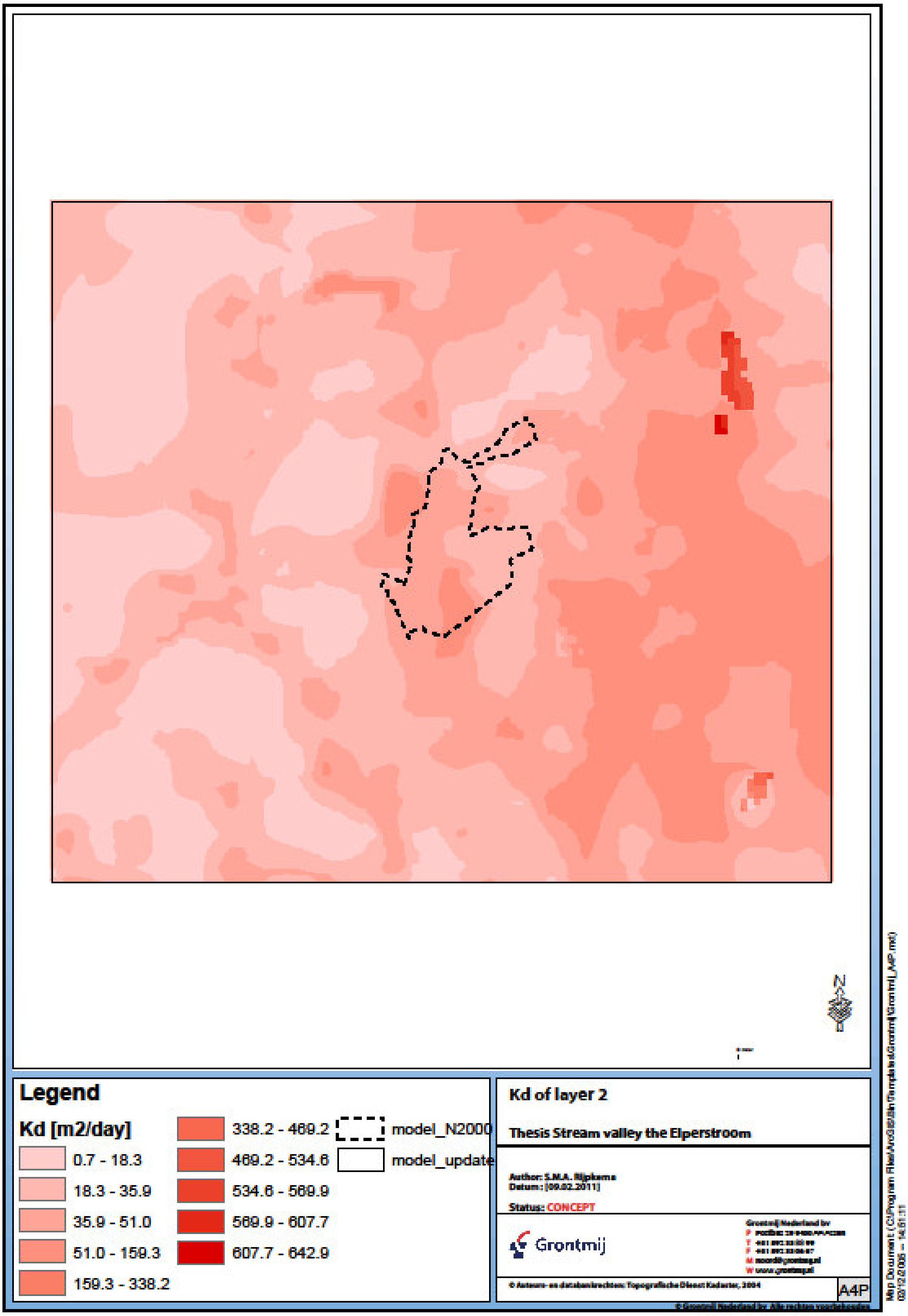
Legend
Kd [m2/day]
0.7 - 18.3
18.3 - 35.9
35.9 - 51.0
51.0 - 159.3
159.3 - 338.2
338.2 - 469.2
469.2 - 534.6
534.6 - 569.9
569.9 - 607.7
607.7 - 642.9
model_N2000
model_update
N
Kd of layer 2
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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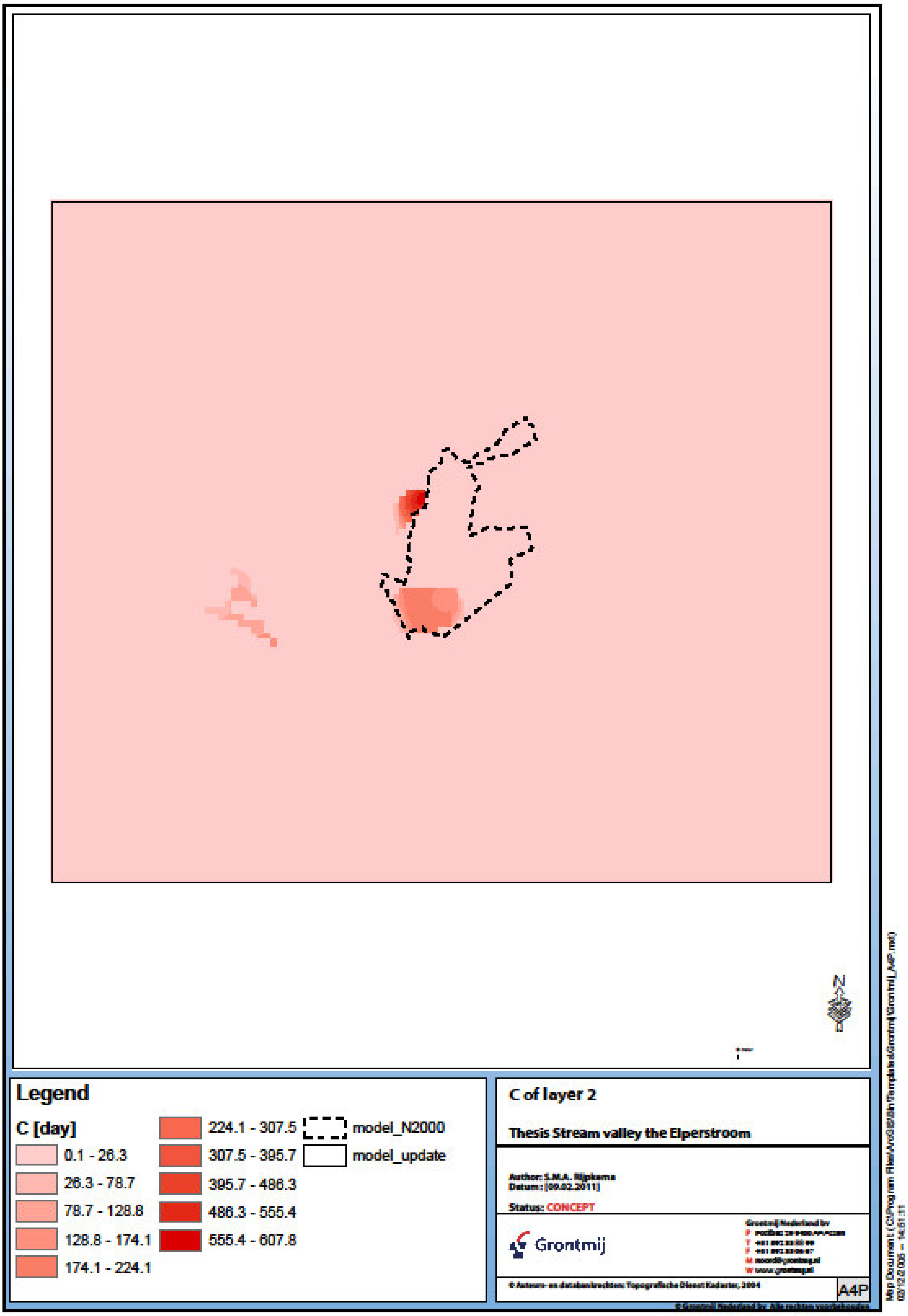
V 3


N
Legend
C [day]
0.1 - 26.3
26.3 - 78.7
78.7 - 128.8
128.8 - 174.1
174.1 - 224.1
224.1 - 307.5
307.5 - 395.7
395.7 - 486.3
486.3 - 555.4
555.4 - 607.8
model_N2000
model_update
C of layer 2
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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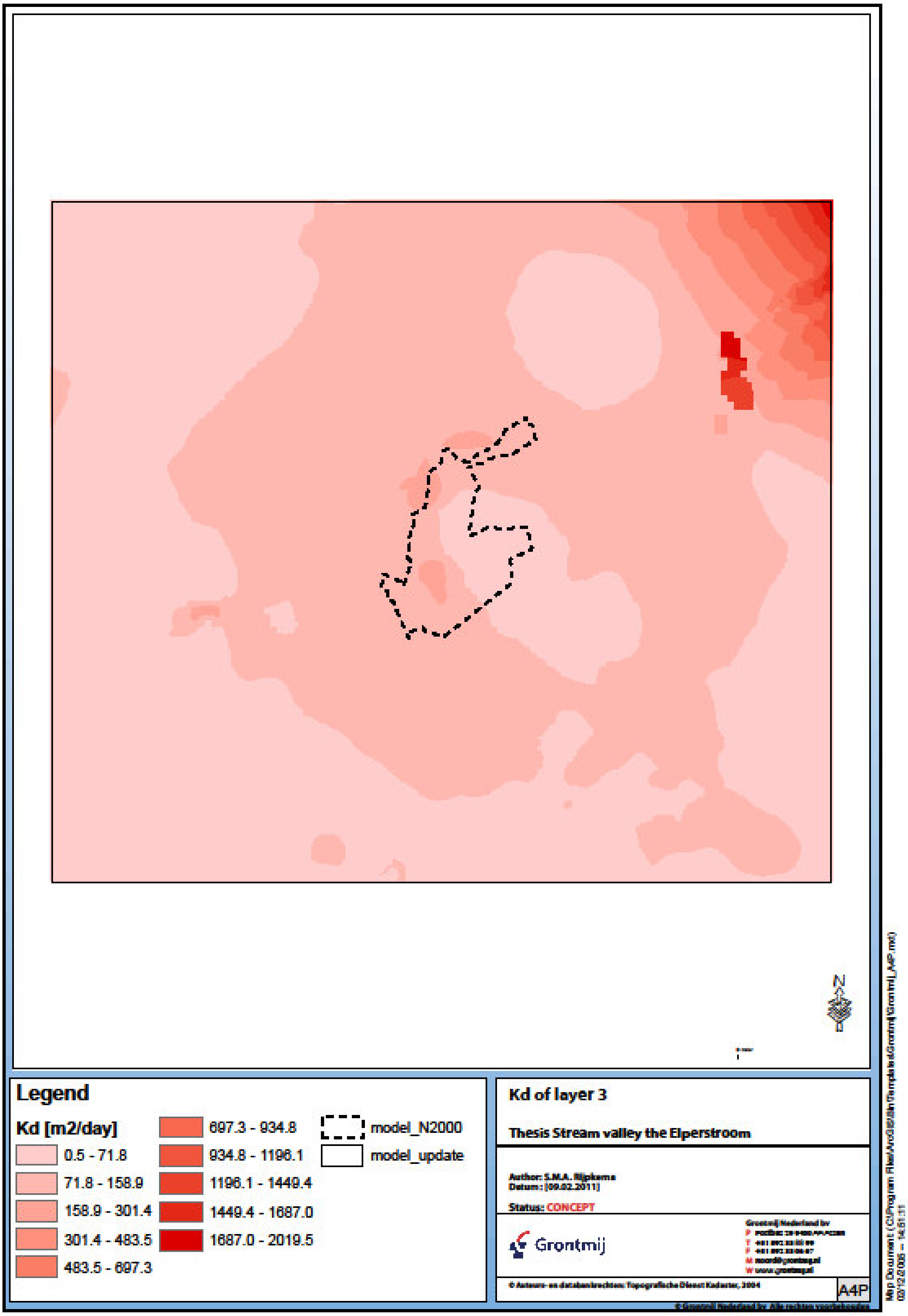
N
Legend
Kd [m2/day]
0.5 - 71.8
71.8 - 158.9
158.9 - 301.4
301.4 - 483.5
483.5 - 697.3
697.3 - 934.8
934.8 - 1196.1
1196.1 - 1449.4
1449.4 - 1687.0
1687.0 - 2019.5
model_N2000
model_update
Kd of layer 3
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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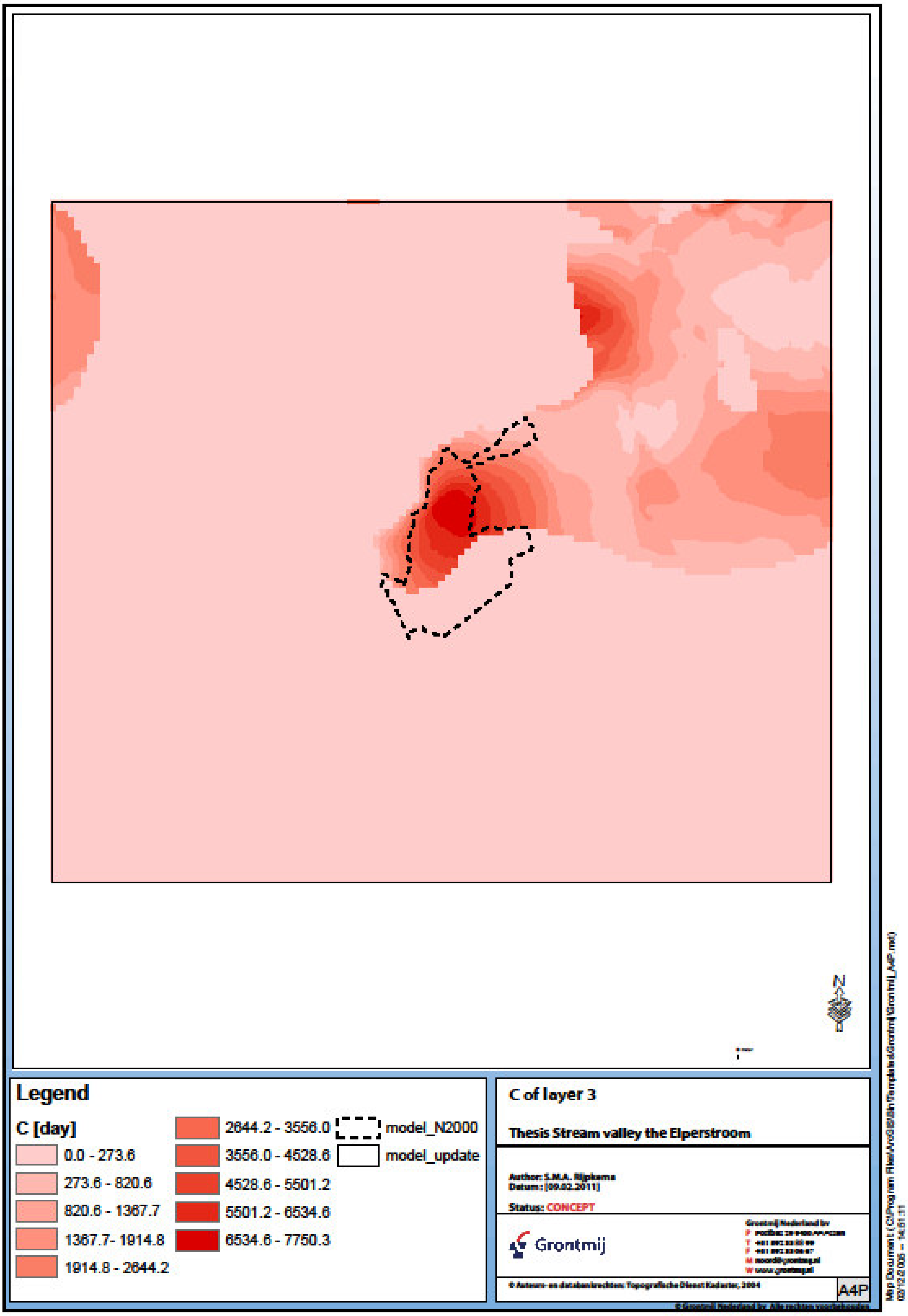
V 5


N
Legend
C [day]
0.0 - 273.6
273.6 - 820.6
820.6 - 1367.7
1367.7- 1914.8
1914.8 - 2644.2
2644.2 - 3556.0
3556.0 - 4528.6
4528.6 - 5501.2
5501.2 - 6534.6
6534.6 - 7750.3
model_N2000
model_update
C of layer 3
Thesis Stream valley the Elperstroom
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Datum: [09.02.2011]
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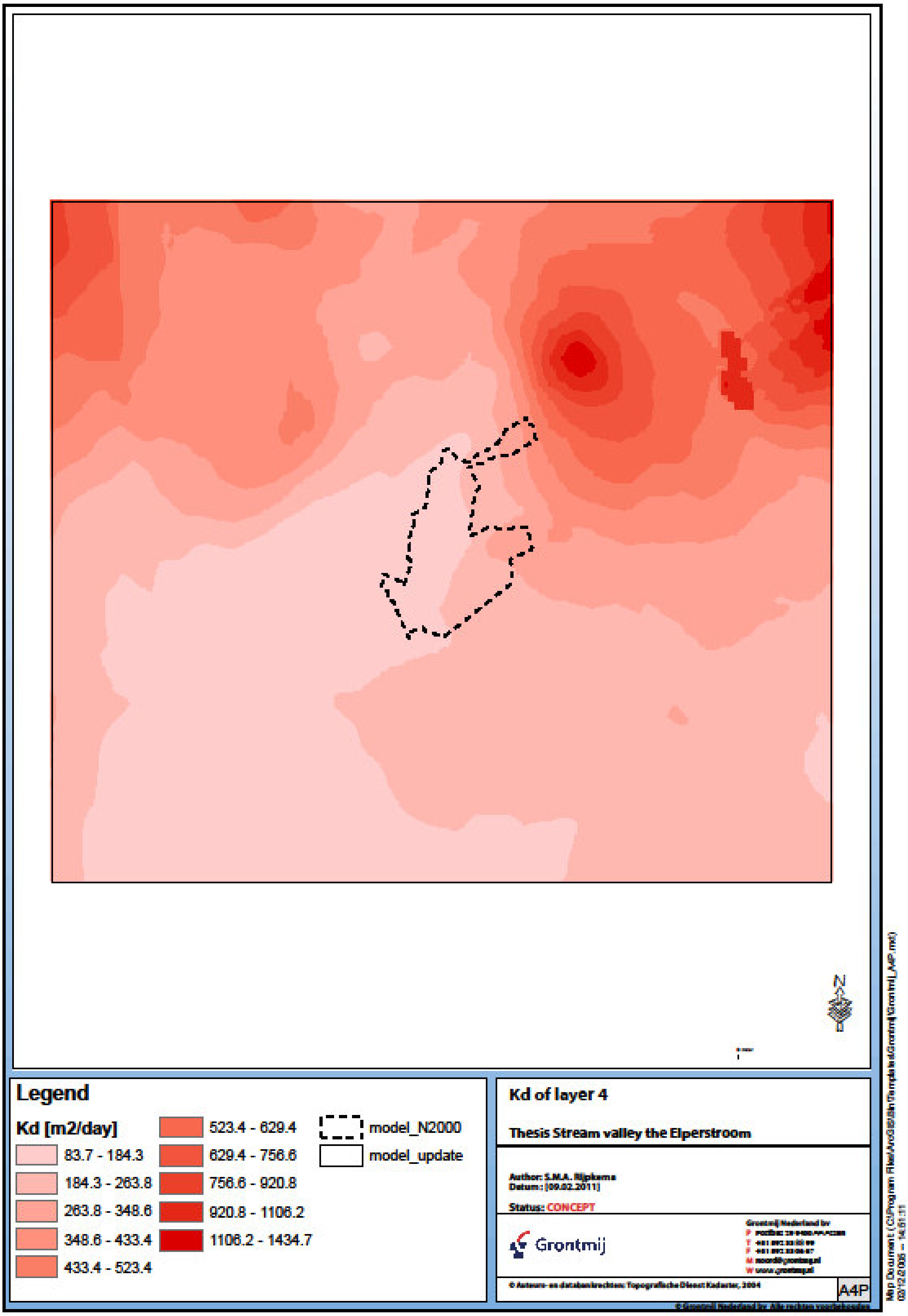
Legend
Kd [m2/day]
83.7 - 184.3
184.3 - 263.8
263.8 - 348.6
348.6 - 433.4
433.4 - 523.4
523.4 - 629.4
629.4 - 756.6
756.6 - 920.8
920.8 - 1106.2
1106.2 - 1434.7
model_N2000
model_update
Kd of layer 4
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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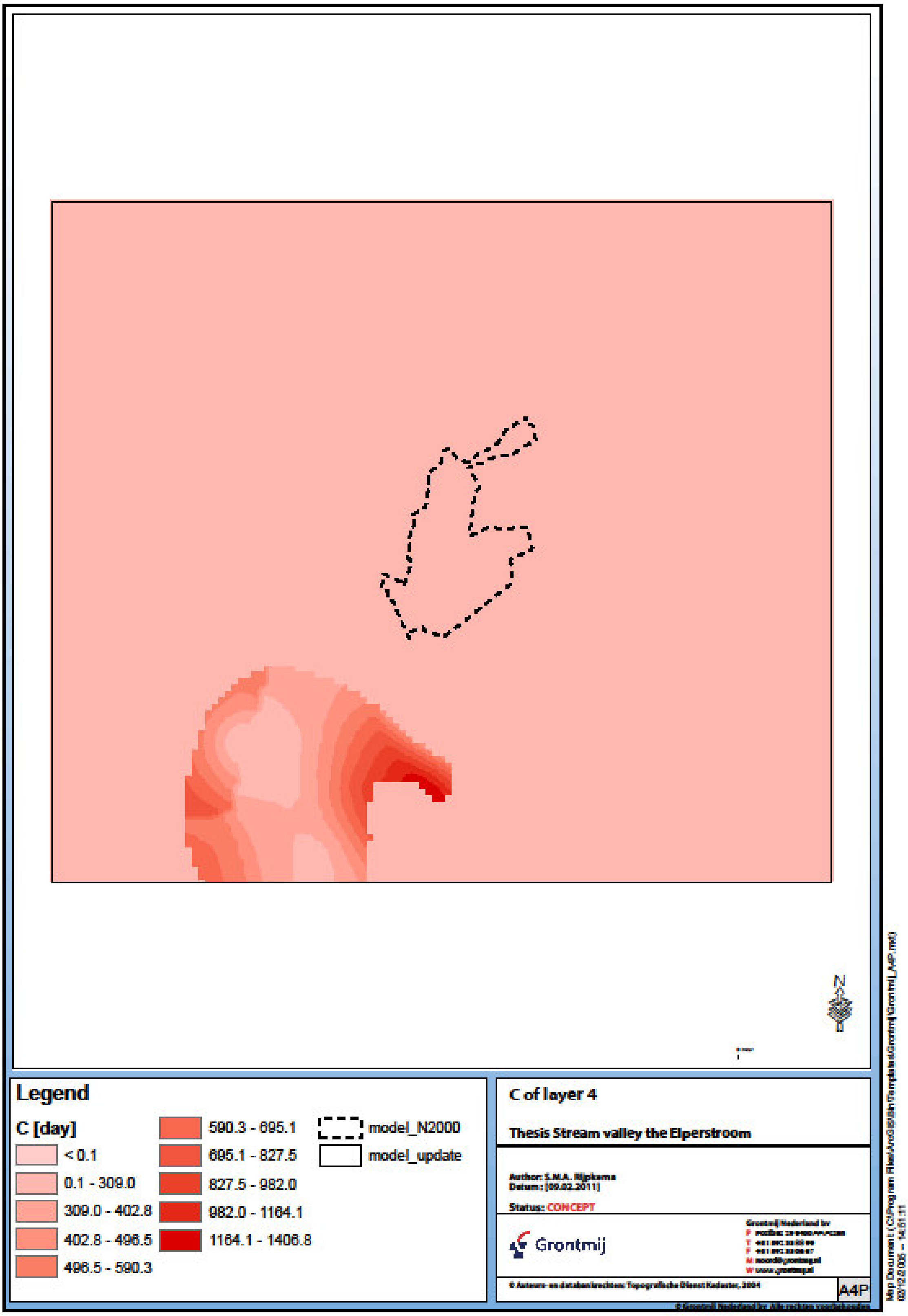
N

V 7


N
Legend
C [day]
< 0.1
0.1 - 309.0
309.0 - 402.8
402.8 - 496.5
496.5 - 590.3
590.3 - 695.1
695.1 - 827.5
827.5 - 982.0
982.0 - 1164.1
1164.1 - 1406.8
model_N2000
model_update
C of layer 4
Thesis Stream valley the Elperstroom
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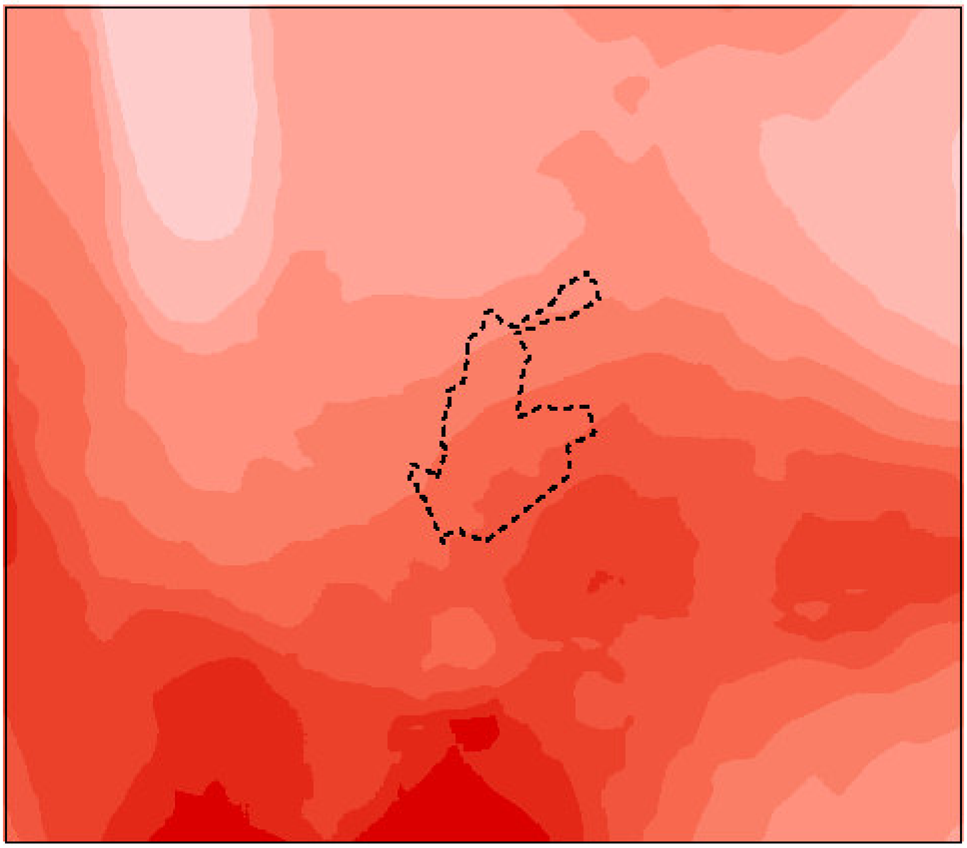
V 8



Legend

Kd [m2/day]

- 🟥 215.4 - 456.4
- 🟥 456.4 - 793.7
- 🟥 793.7 - 1095.0
- 🟥 1095.0 - 1372.1
- 🟥 1372.1 - 1649.2
- 🟥 1649.2 - 1902.3
- 🟥 1902.3 - 2107.1
- 🟥 2107.1 - 2324.0
- 🟥 2324.0 - 2613.2
- 🟥 2613.2 - 3288.0
- ⬚ model_N2000
- ☐ model_update

Kd of layer 5

Thesis Stream valley the Elperstroom

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Datum: [09.02.2011]

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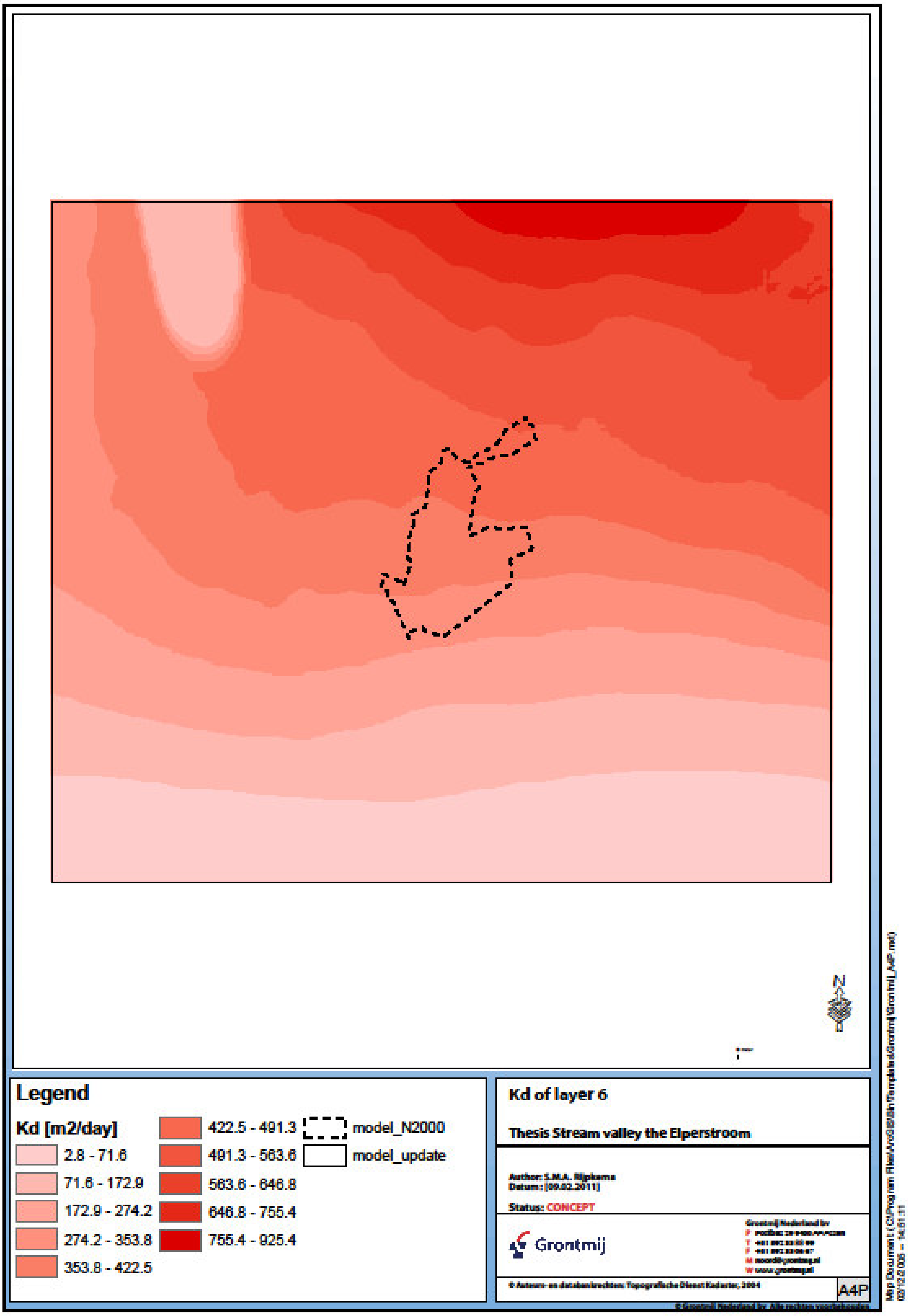
V 9


N
Legend
Kd [m2/day]
2.8 - 71.6
71.6 - 172.9
172.9 - 274.2
274.2 - 353.8
353.8 - 422.5
422.5 - 491.3
491.3 - 563.6
563.6 - 646.8
646.8 - 755.4
755.4 - 925.4
model_N2000
model_update
Kd of layer 6
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
Status: CONCEPT
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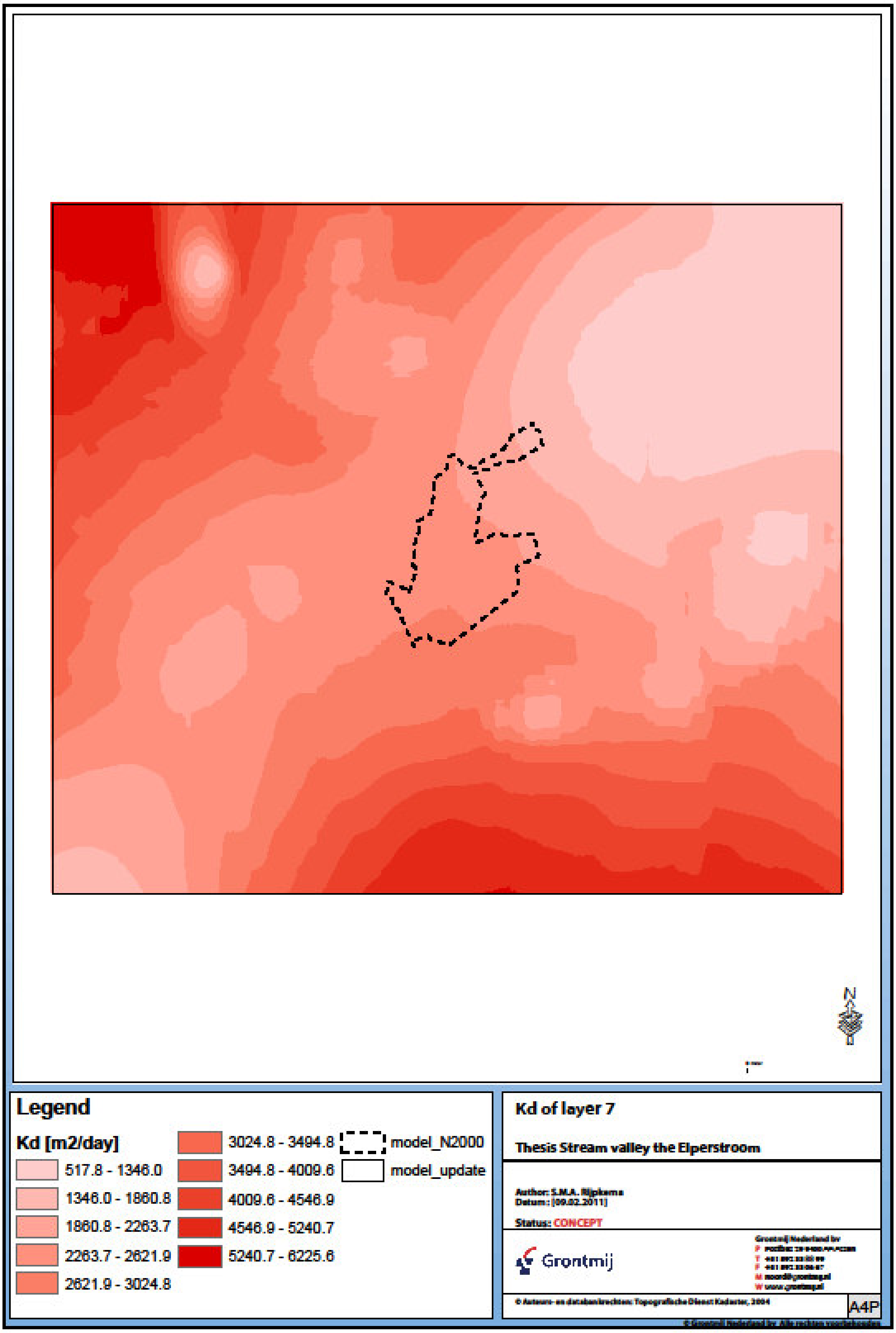
V 10


N
Legend
Kd [m2/day]
517.8 - 1346.0
1346.0 - 1860.8
1860.8 - 2263.7
2263.7 - 2621.9
2621.9 - 3024.8
3024.8 - 3494.8
3494.8 - 4009.6
4009.6 - 4546.9
4546.9 - 5240.7
5240.7 - 6225.6
model_N2000
model_update
Kd of layer 7
Thesis Stream valley the Elperstroom
Author: S.M.A. Rijpkema
Datum: [09.02.2011]
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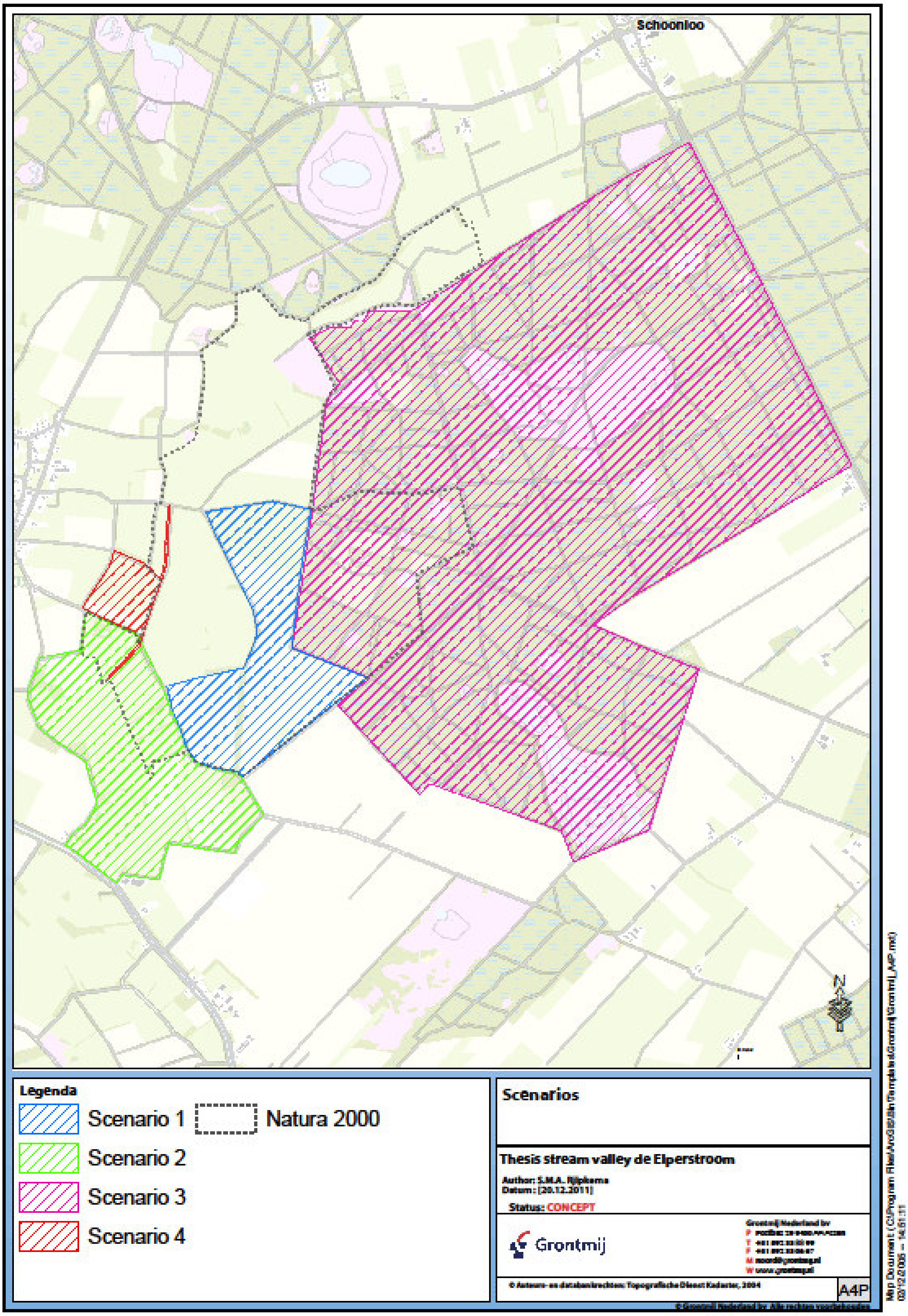
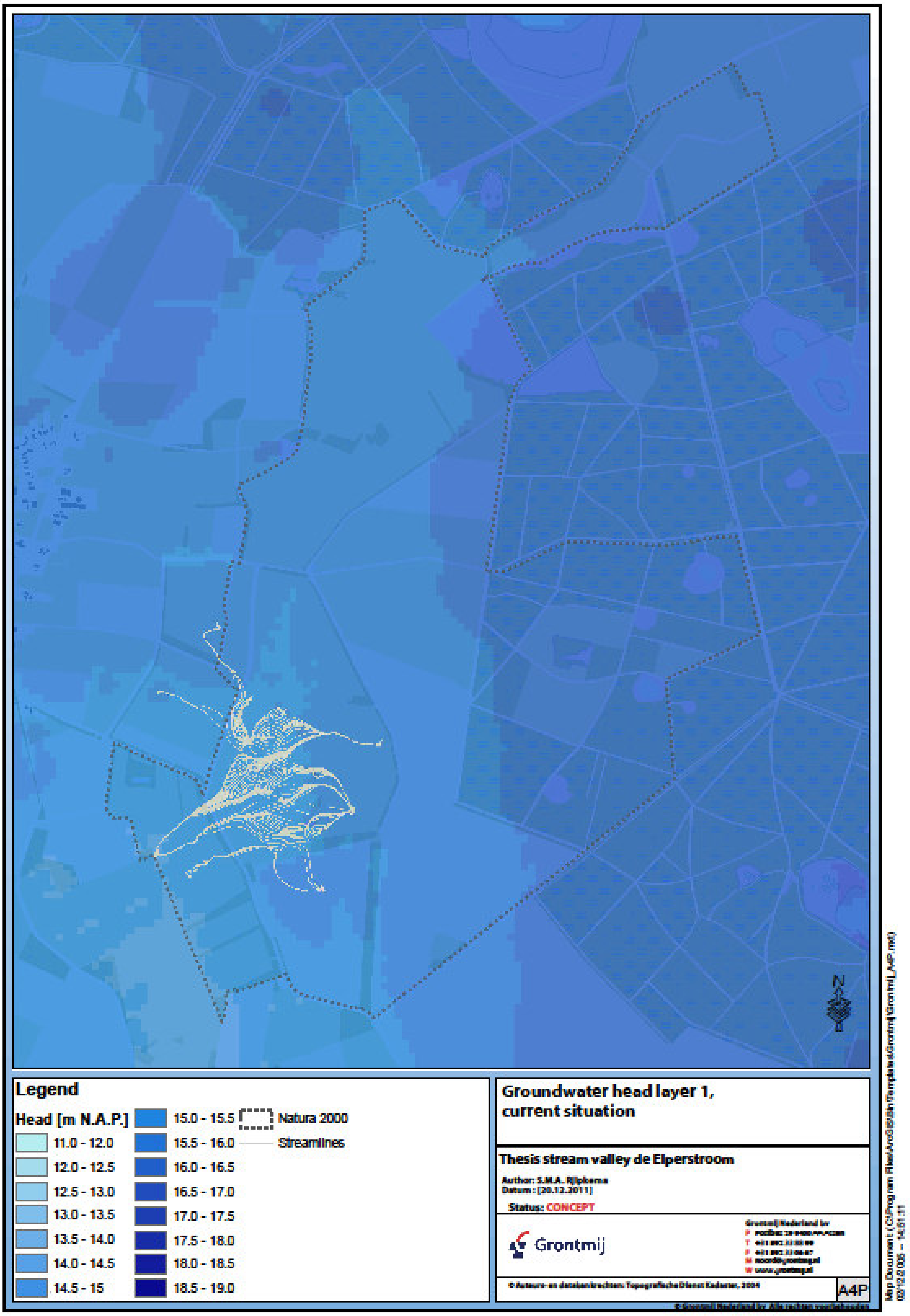
V 11

Appendix VI

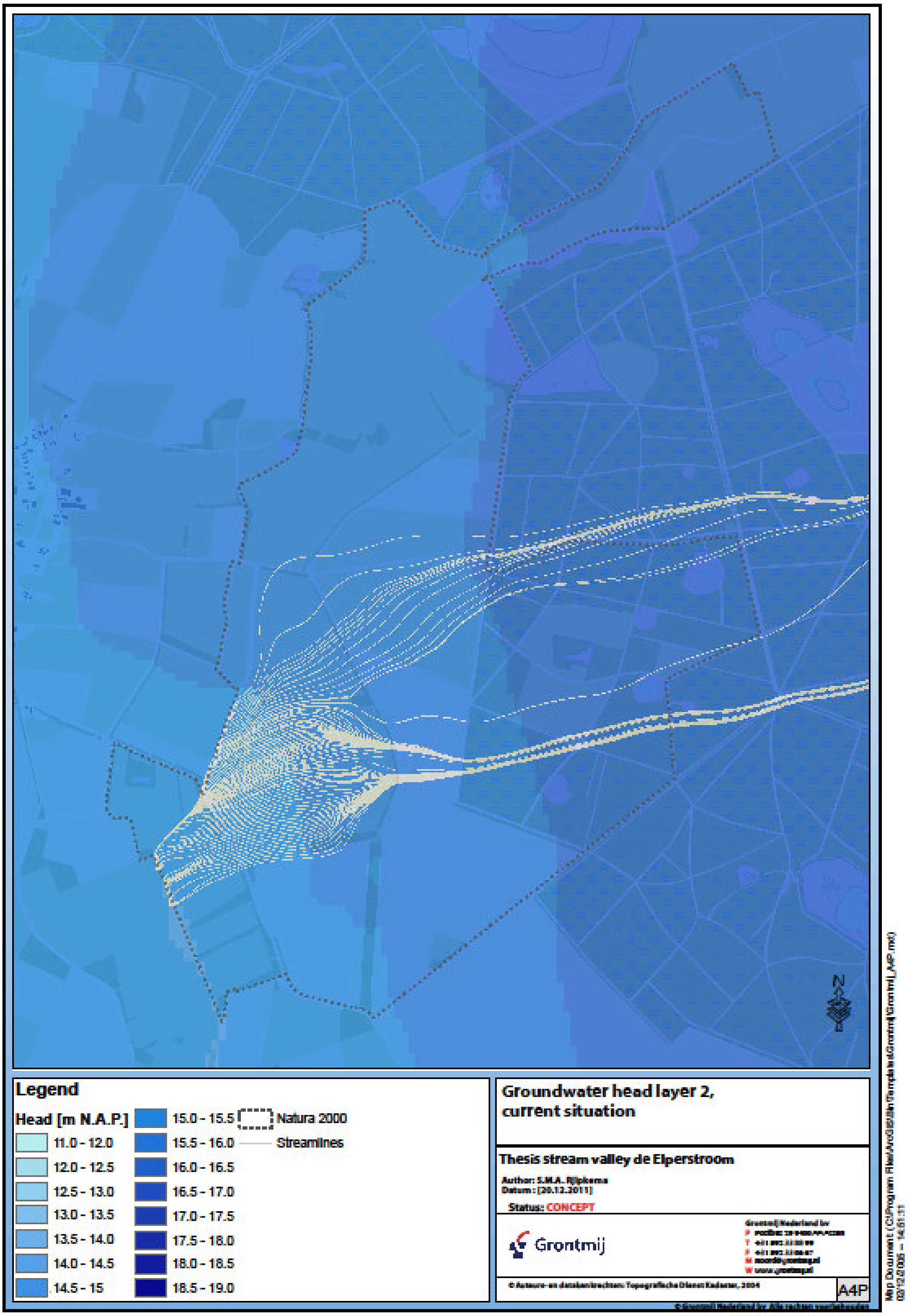
Scenarios



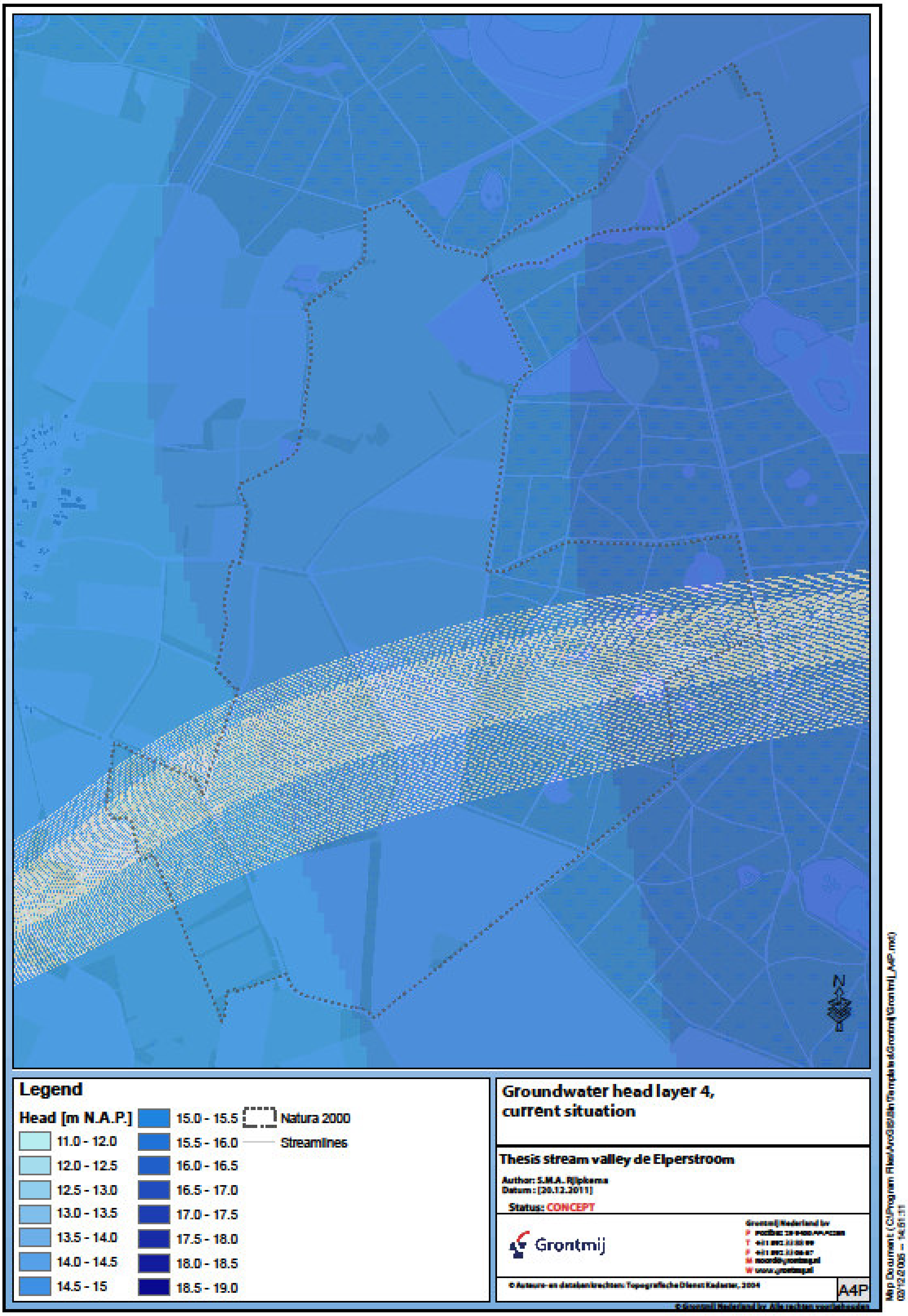
VI 1 Areas affected by scenario



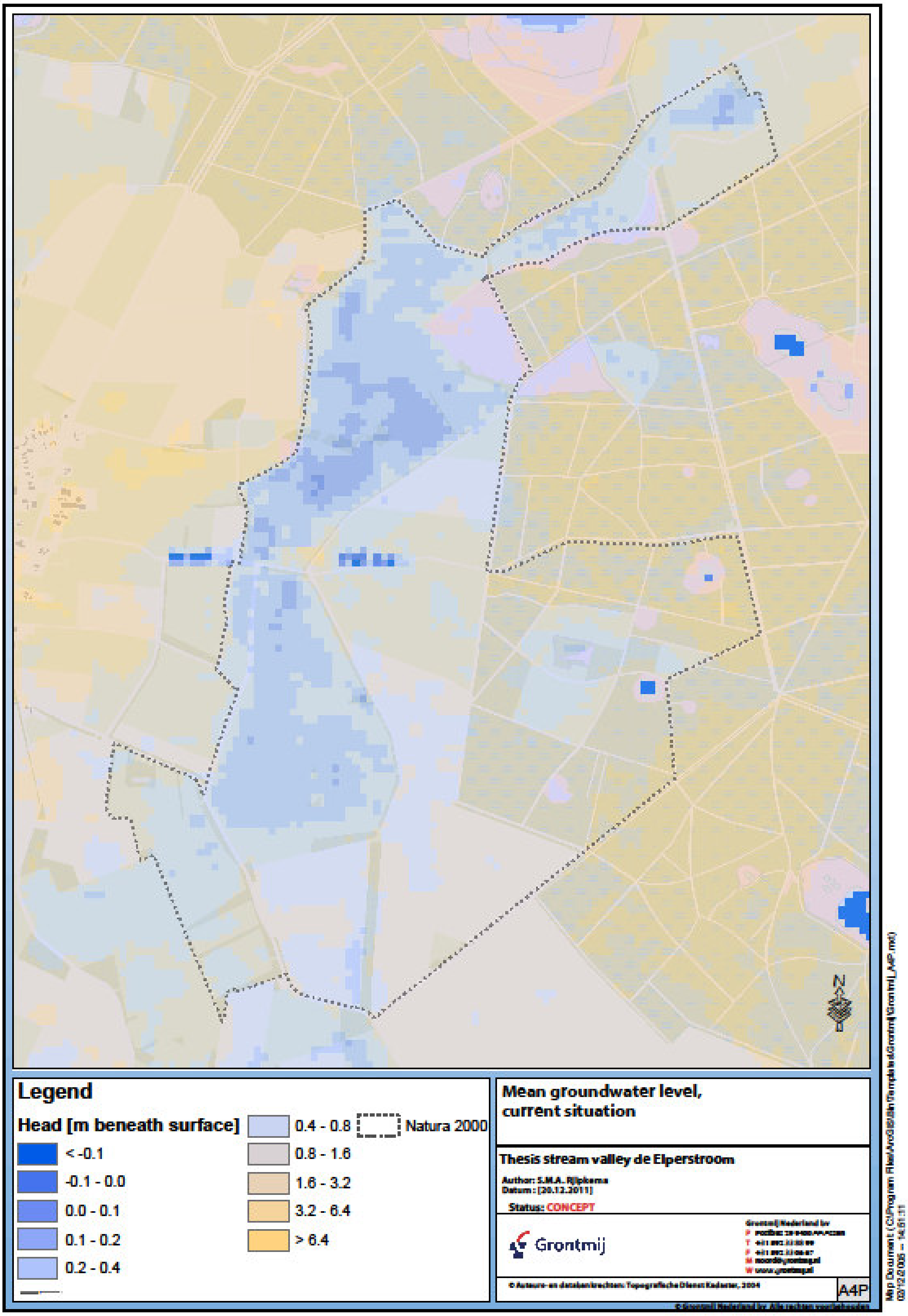
VI 2 Groundwater head layer 1, current situation.



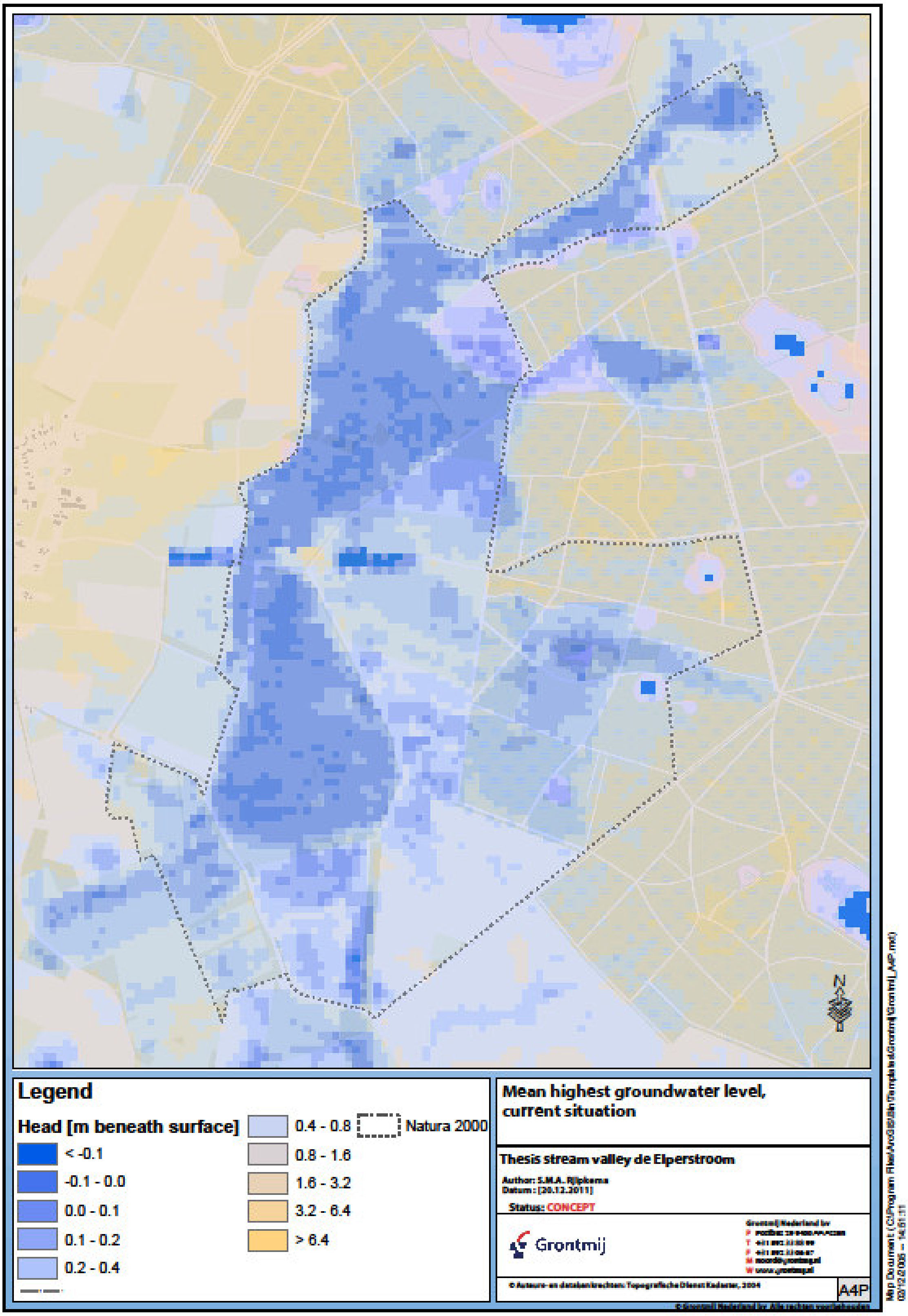
VI 3 Groundwater head layer 2, current situation.



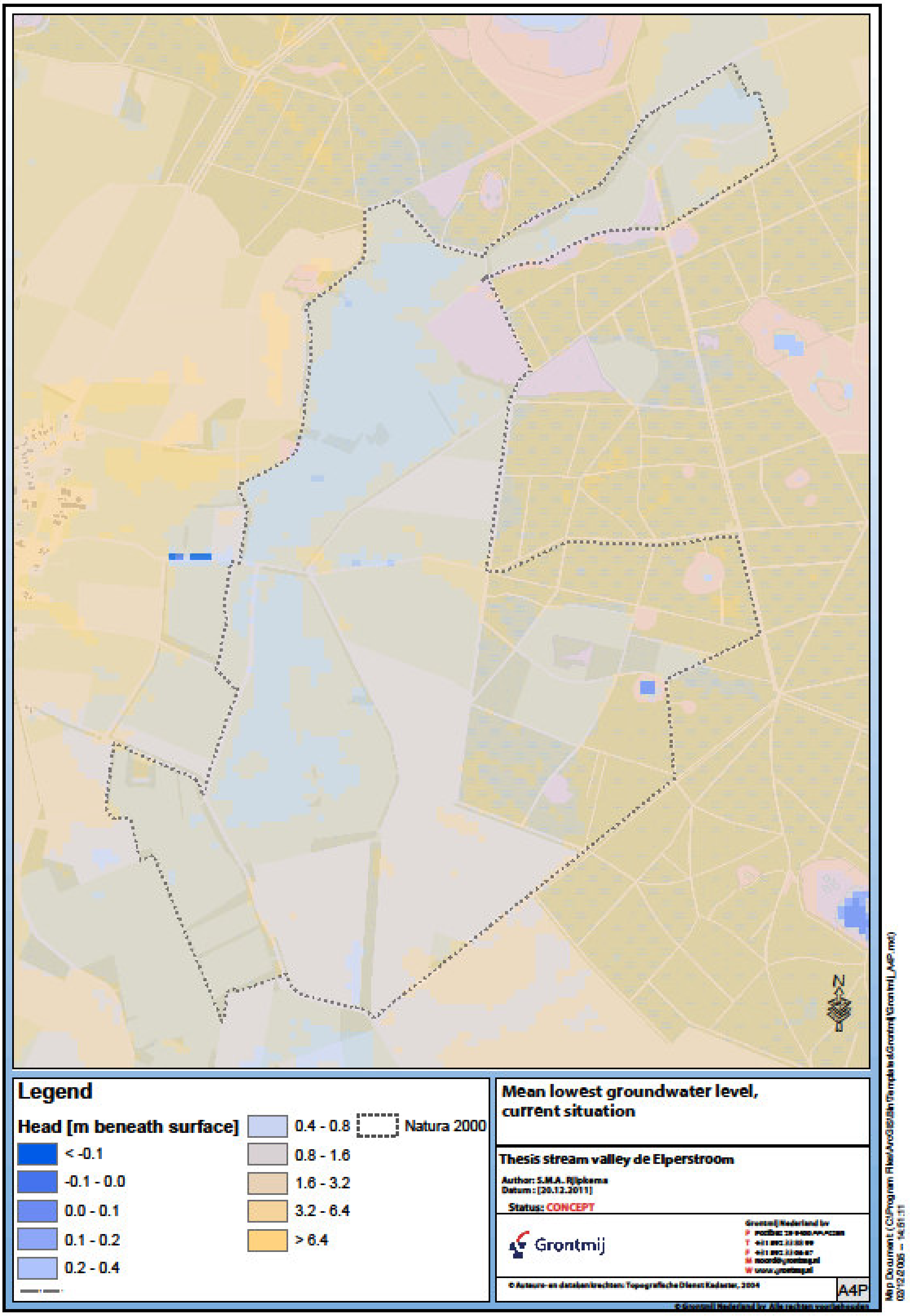
VI 4 Groundwater head layer 4, current situation.



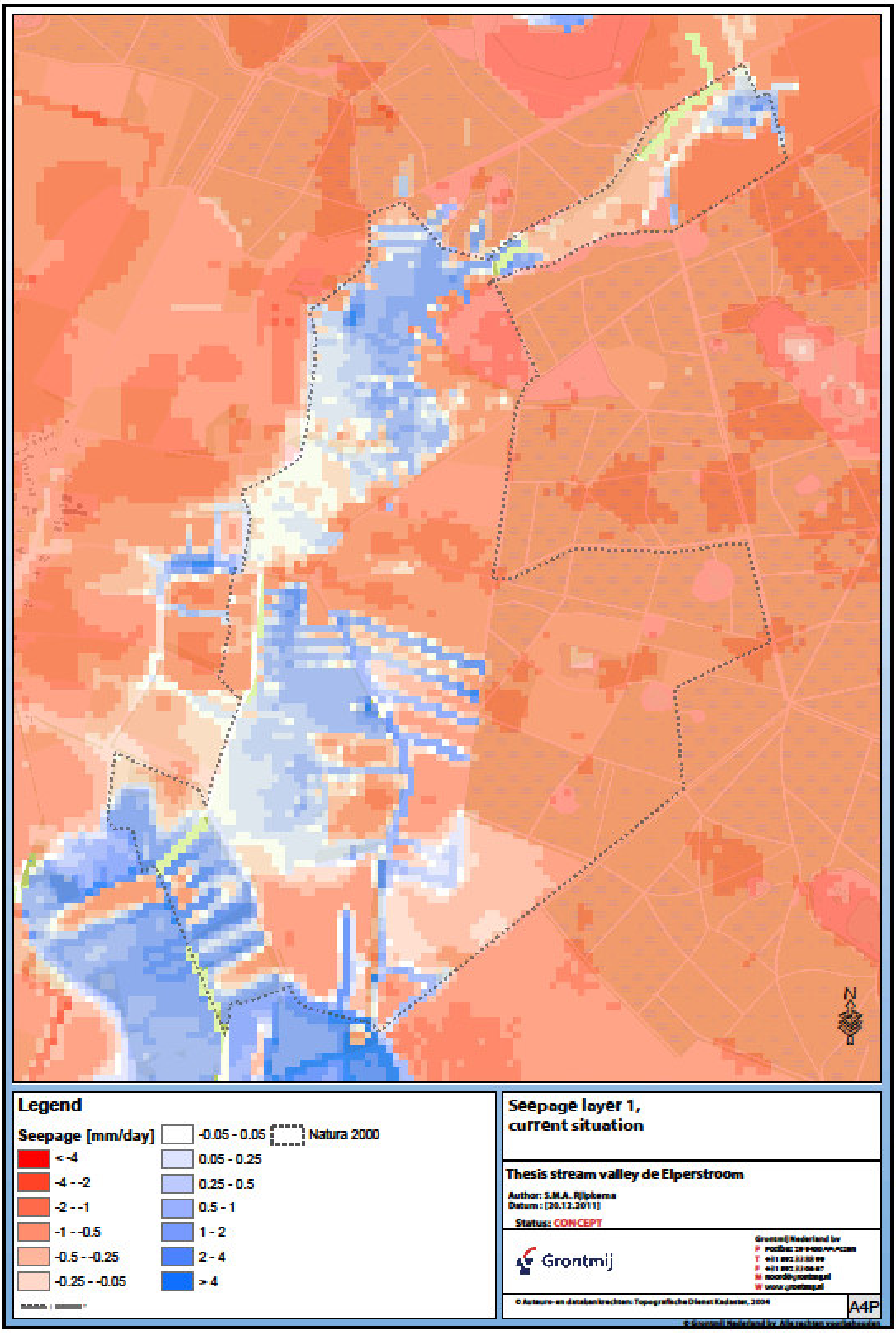
VI 5 Mean groundwater level, current situation.



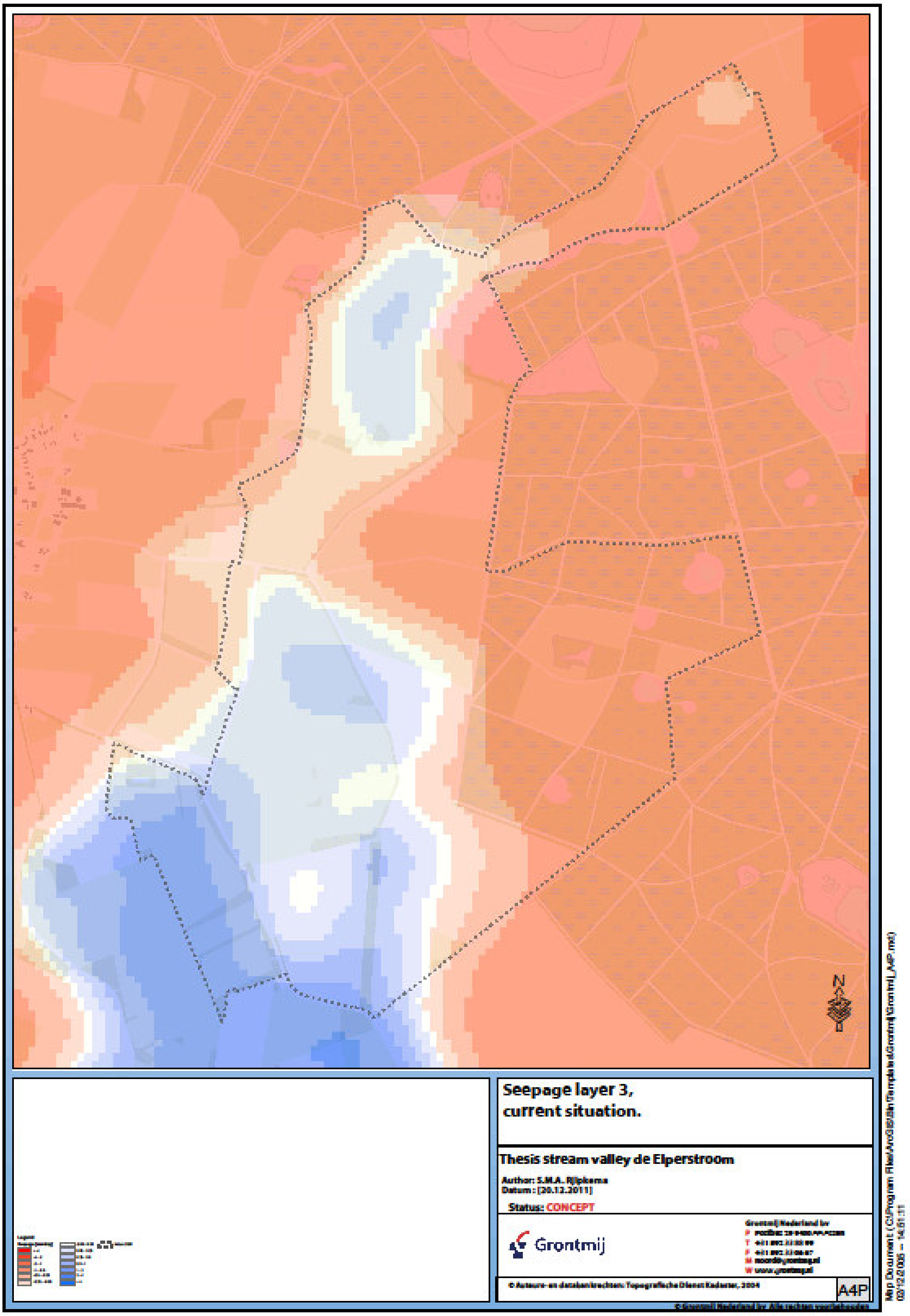
VI 6 Mean highest groundwater level, current situation.



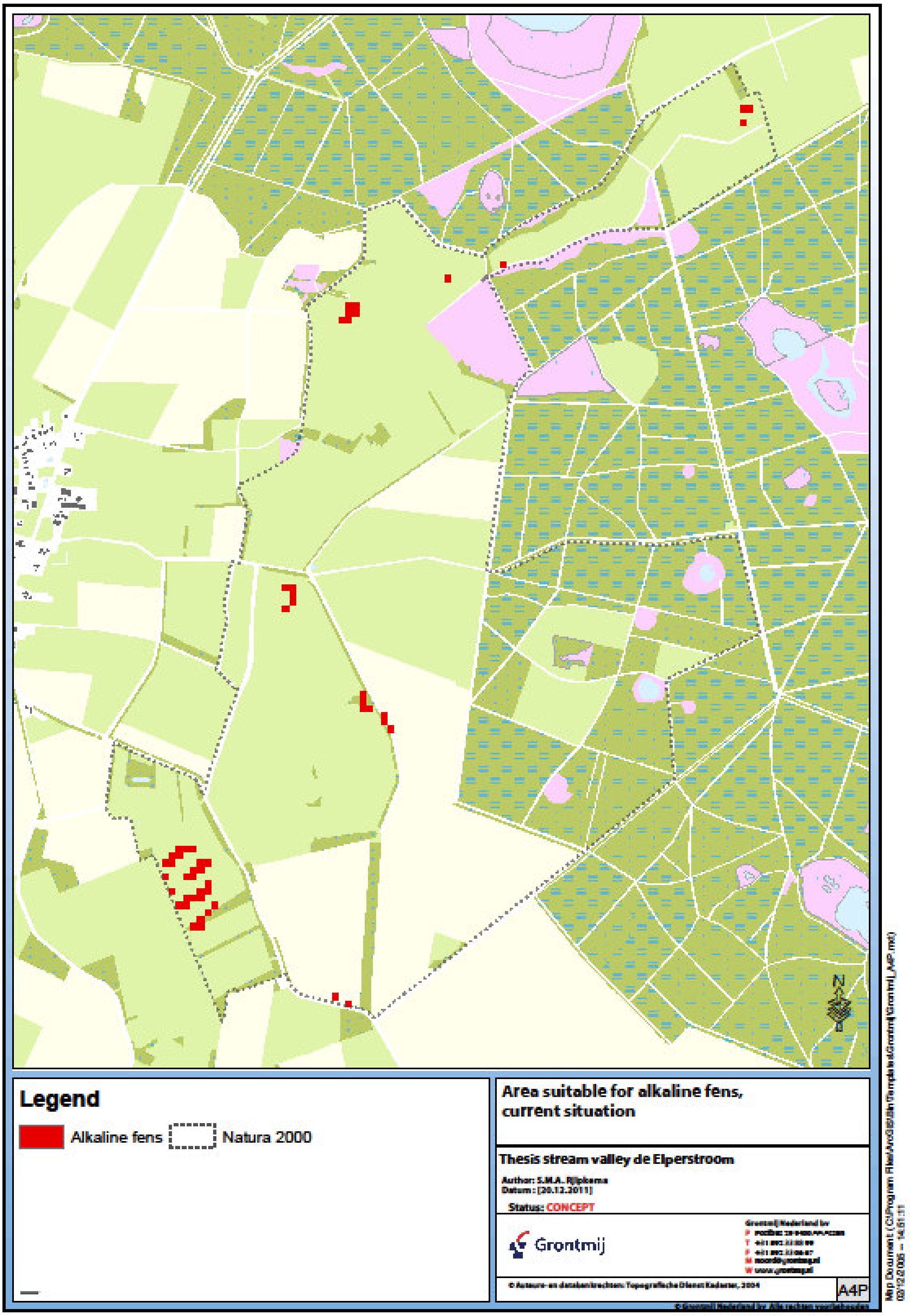
VI 7 Mean lowest groundwater level, current situation.



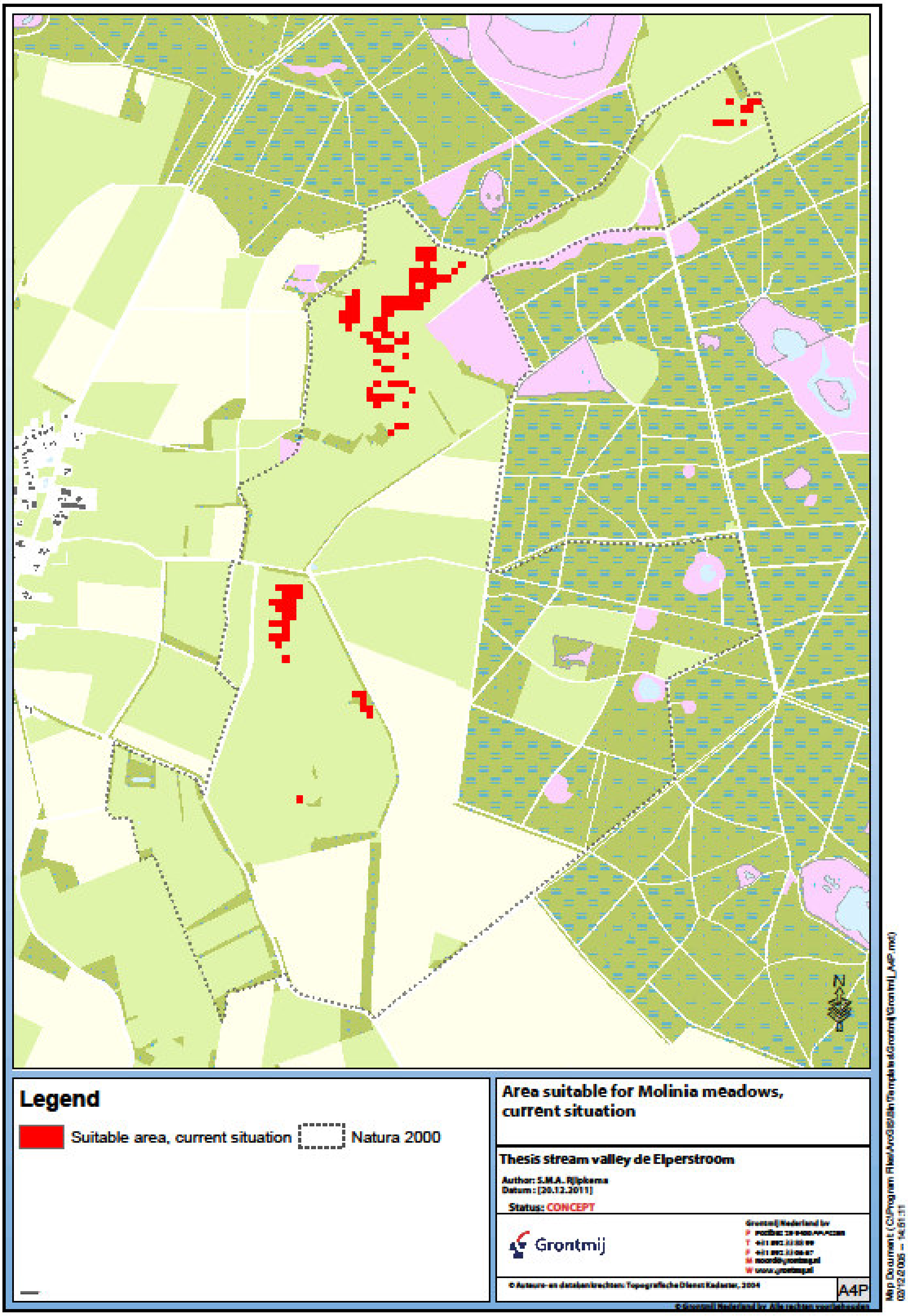
VI 8 Seepage to layer 1, current situation.



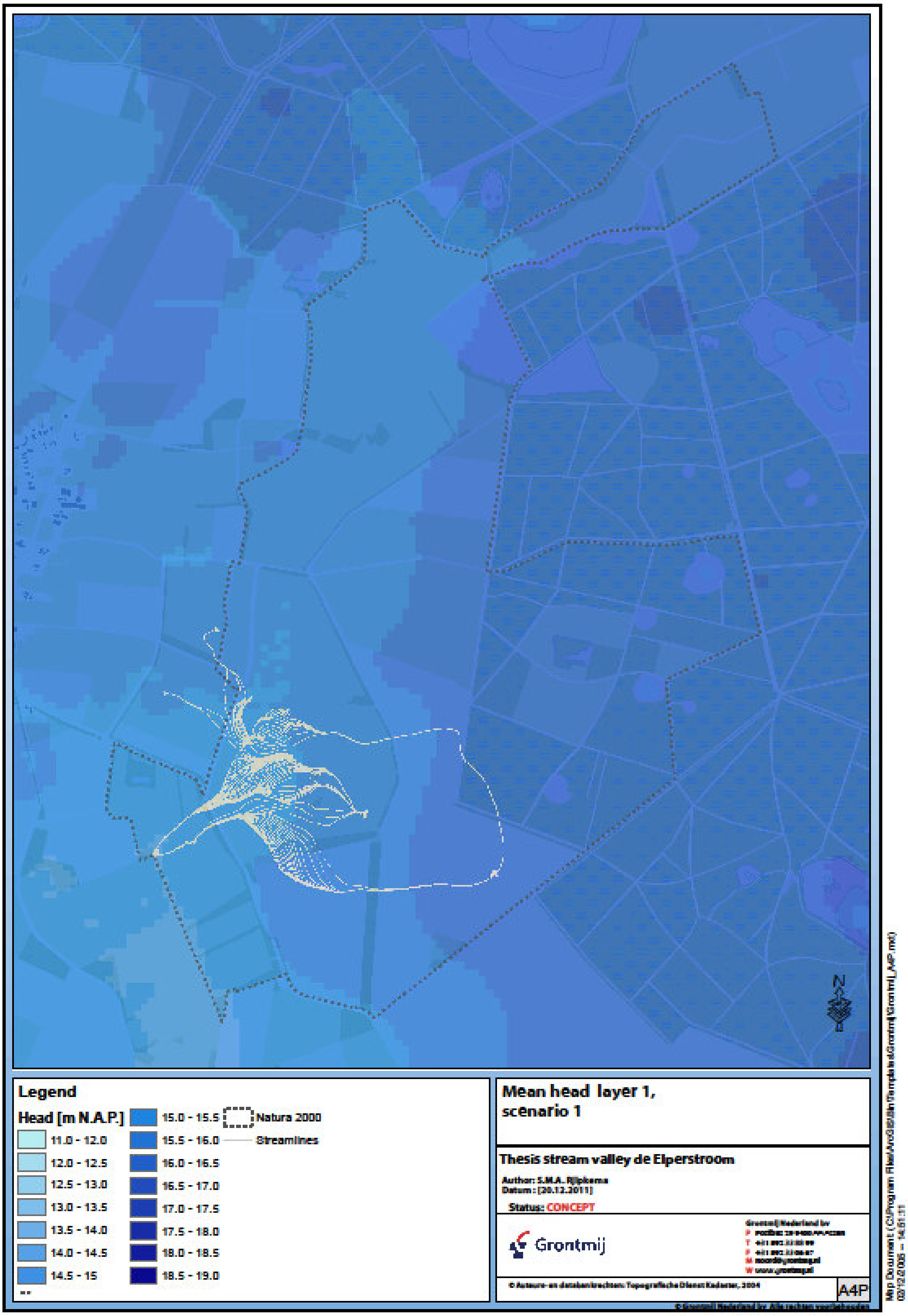
VI 9 Seepage to layer 3, current situation.



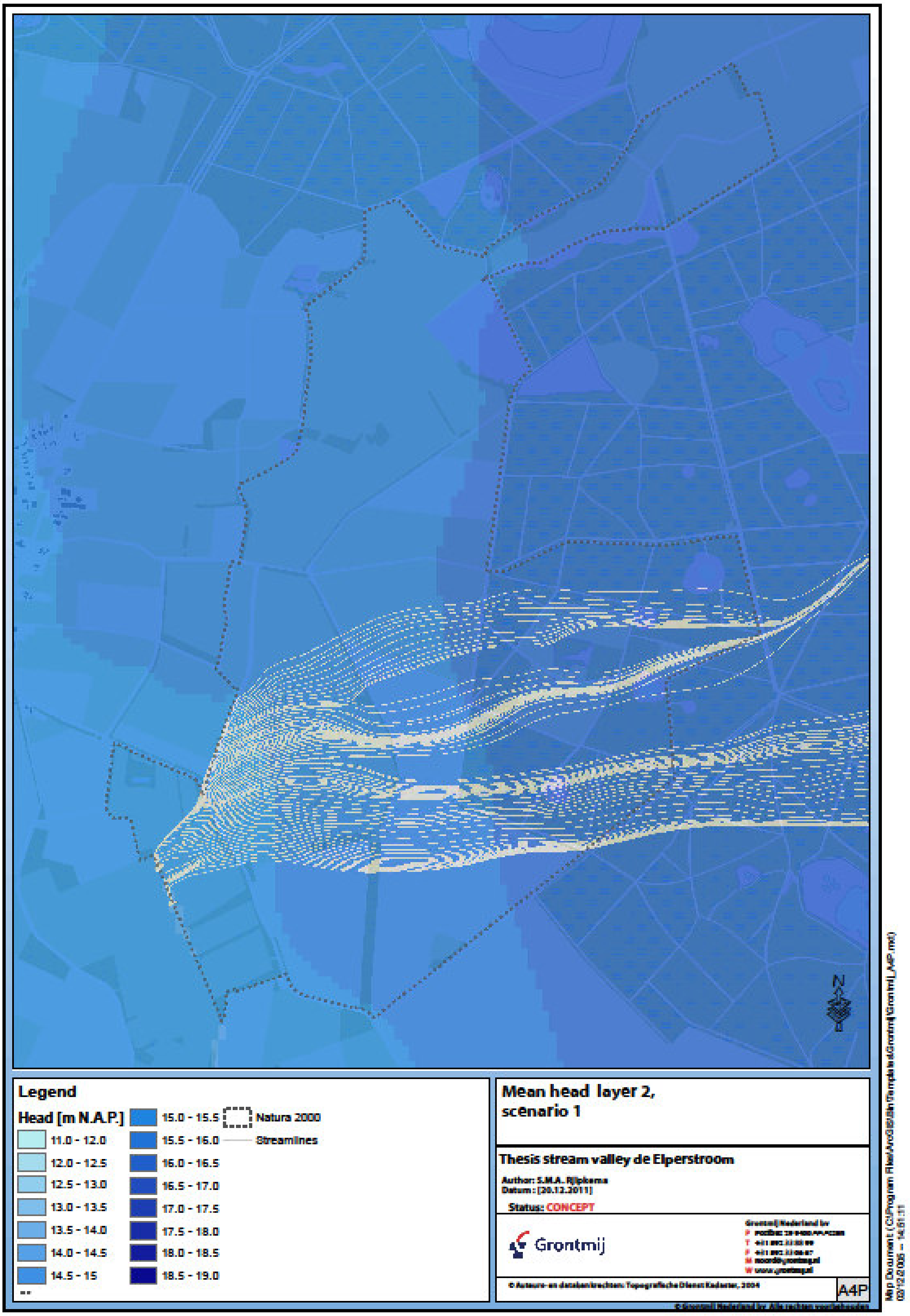
VI 10 Area suitable for alkaline fens, current situation.



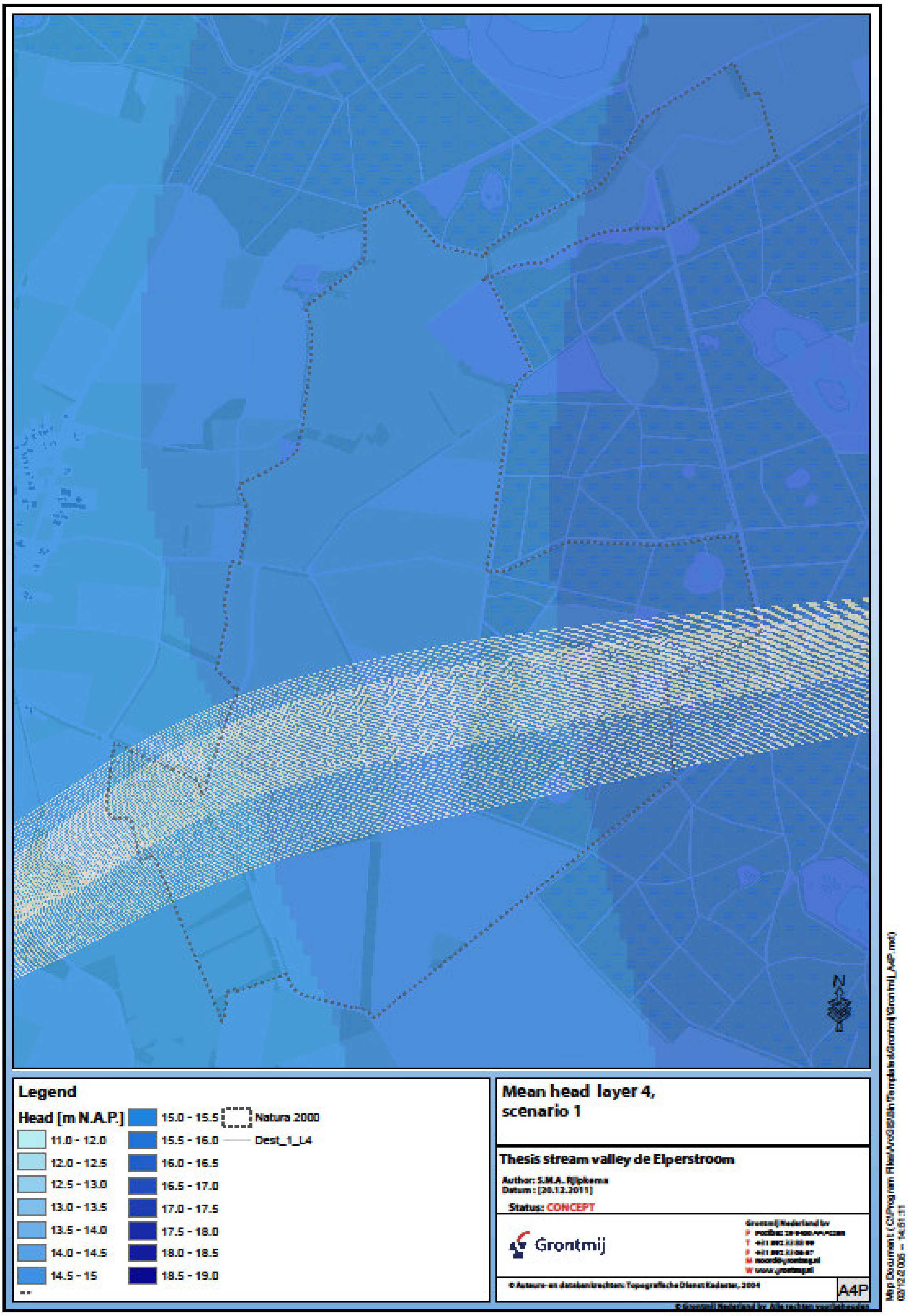
VI 11 Area suitable for Molinia meadows, current situation.



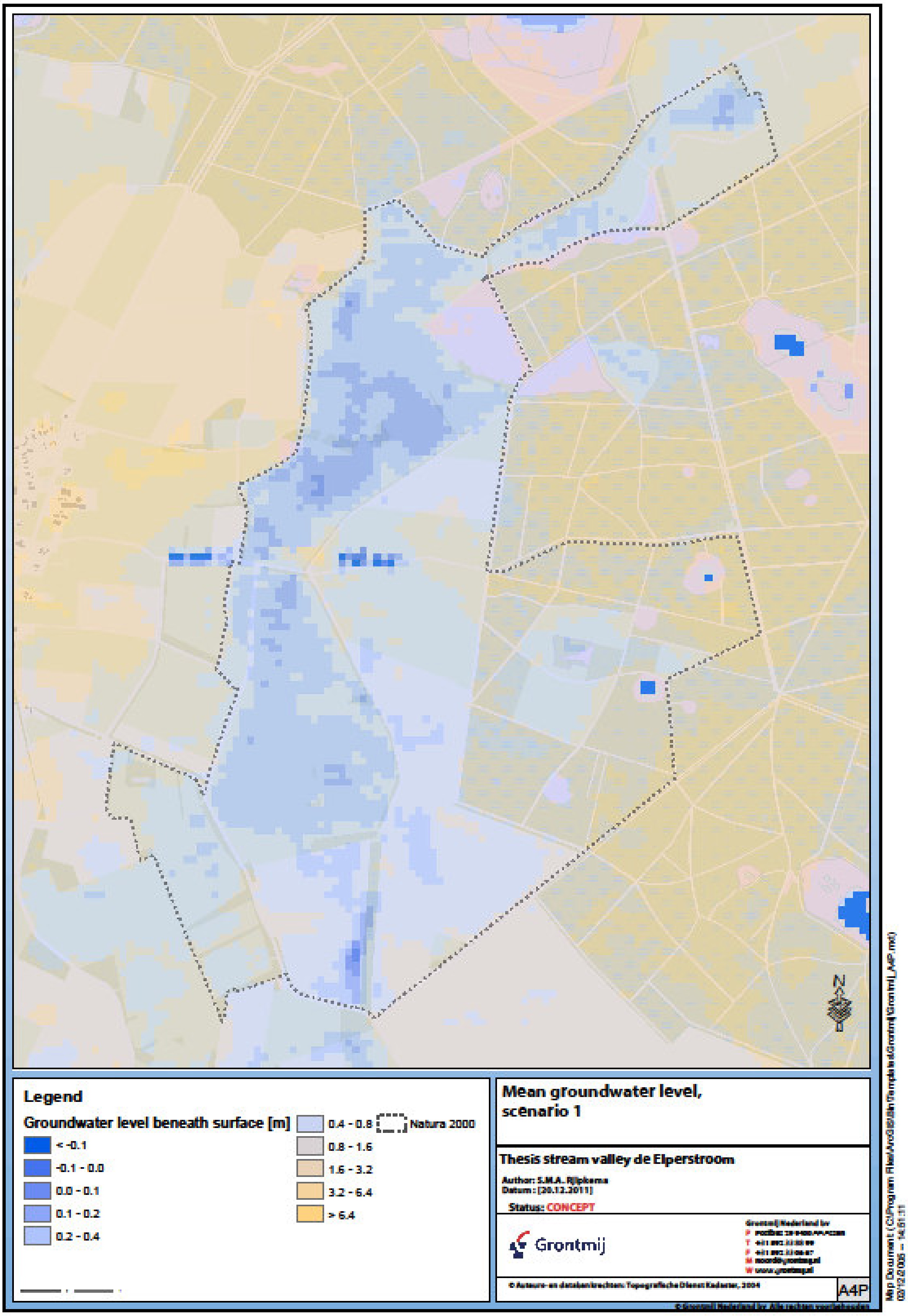
VI 12 Mean head layer 1, scenario 1



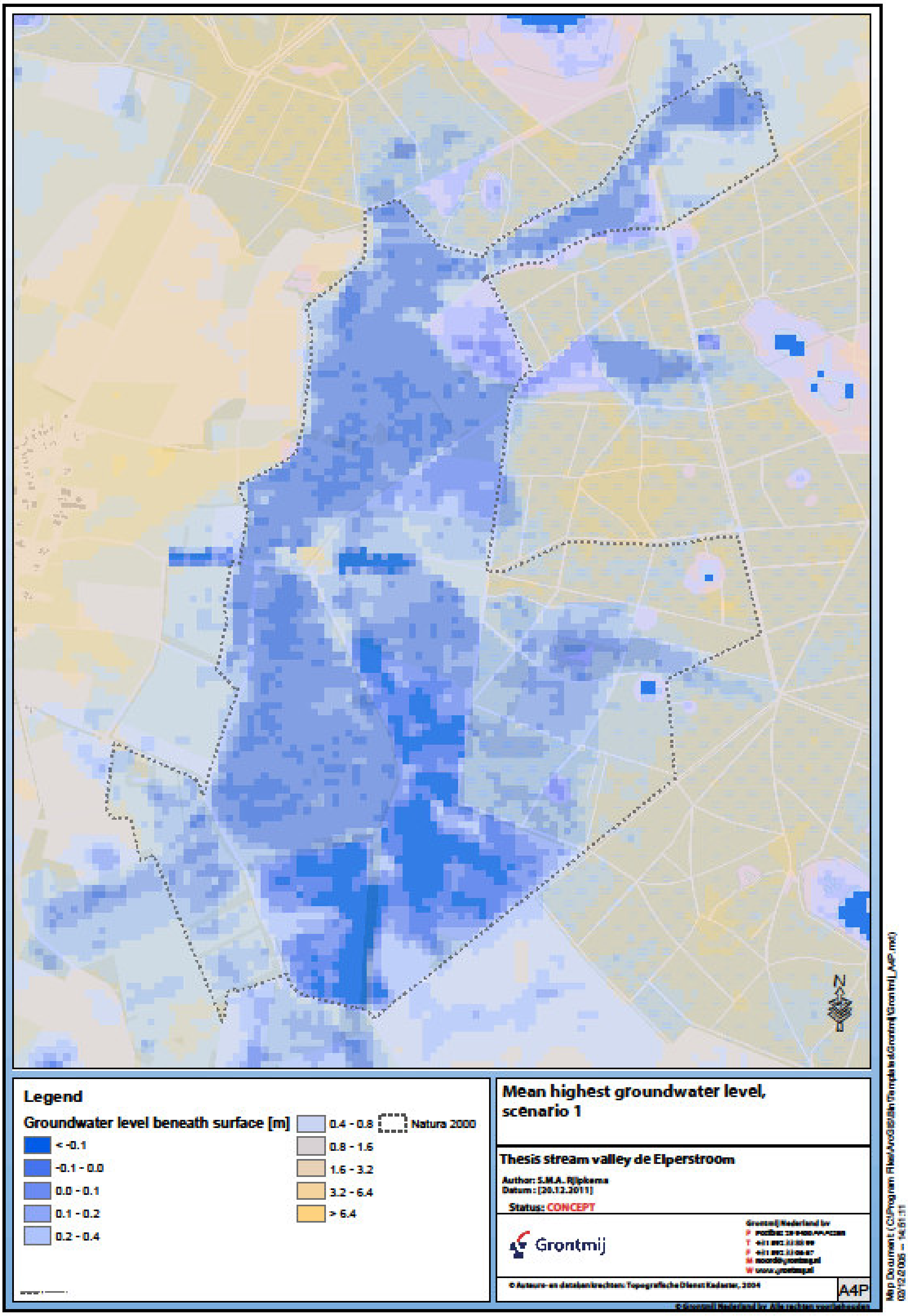
VI 13 Mean head layer 2, scenario 1.



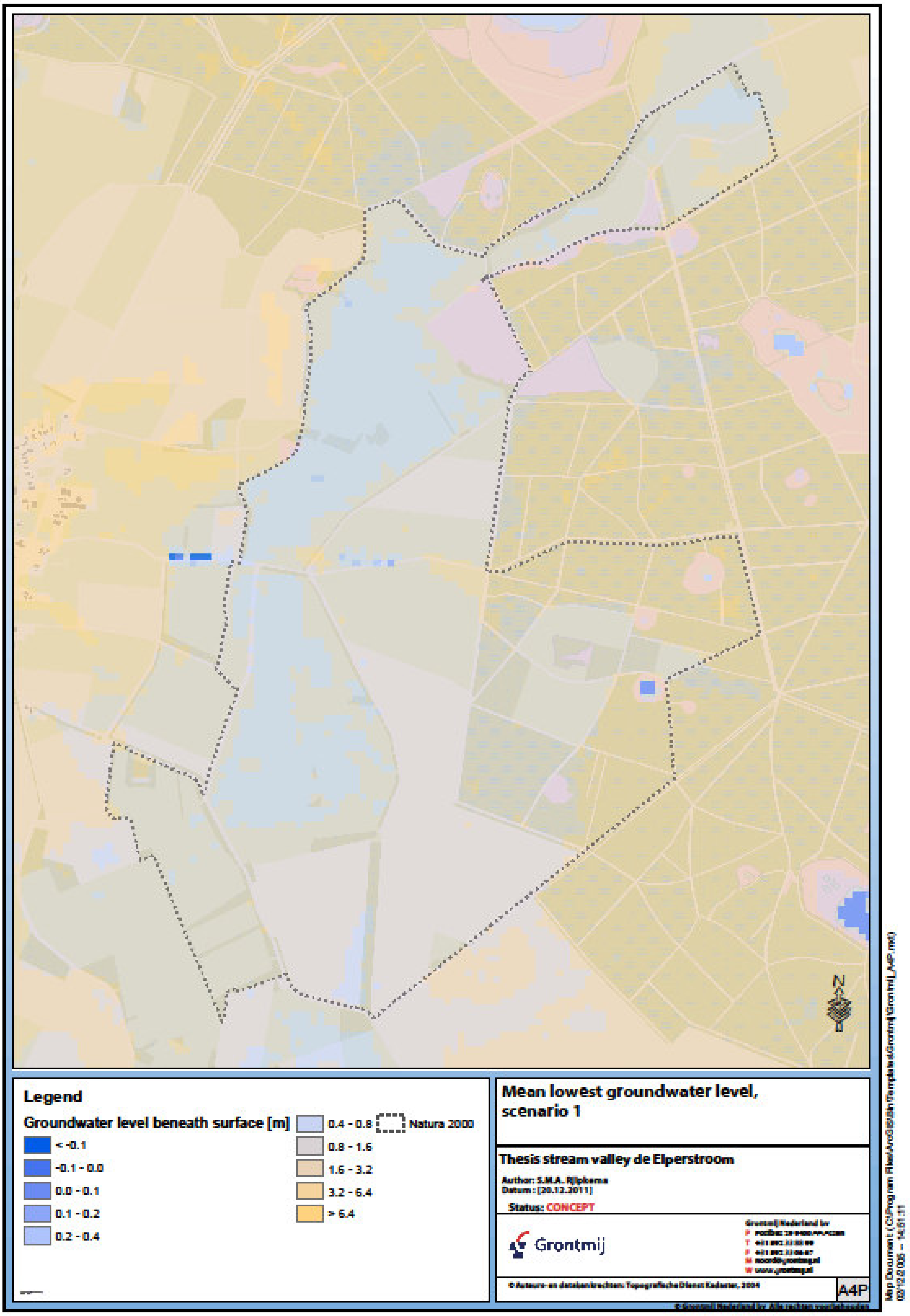
VI 14 Mean head layer 4, scenario 1.



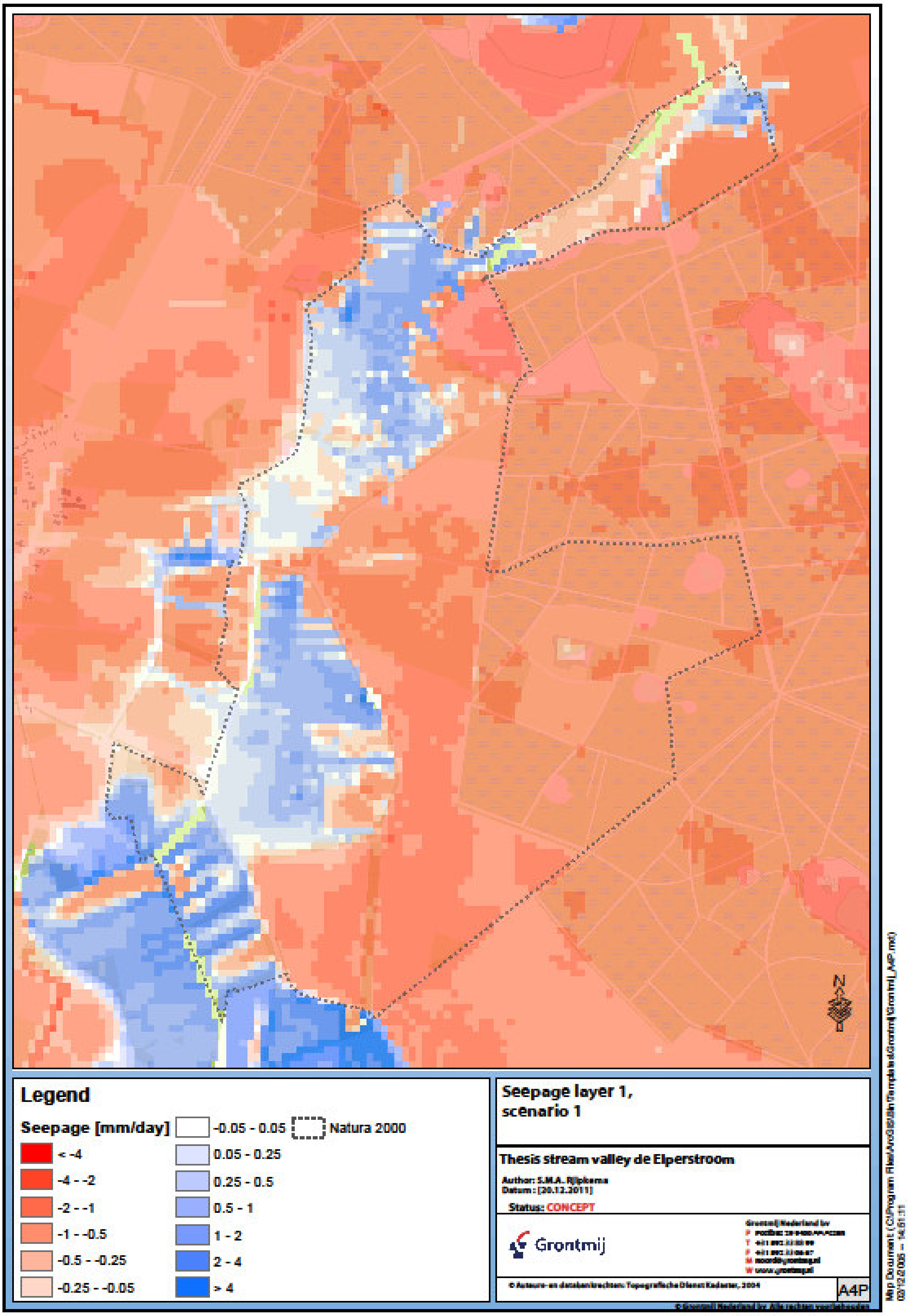
VI 15 Mean groundwater level, scenario 1.



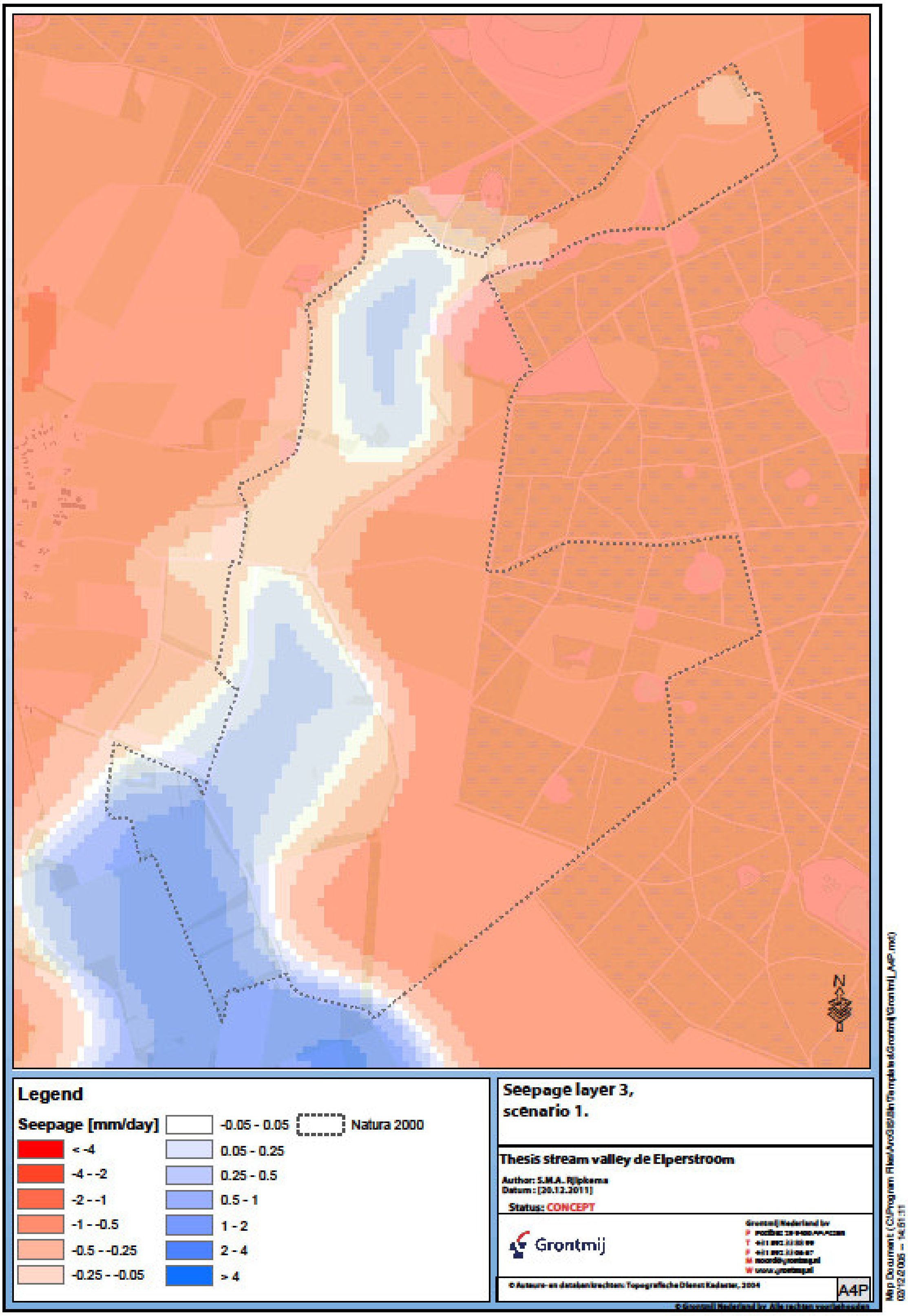
VI 16 Mean highest groundwater level, scenario 1.



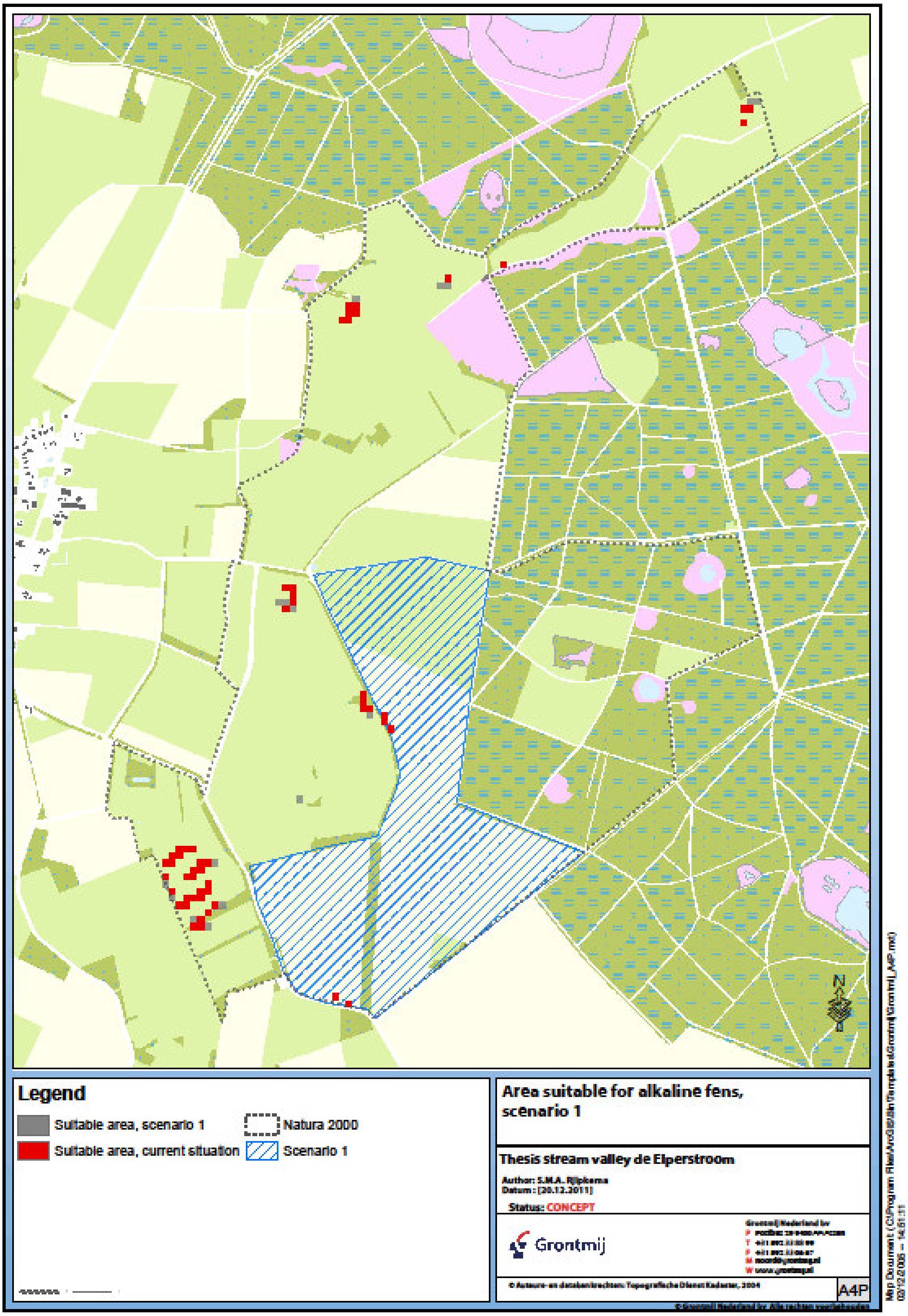
VI 17 Mean lowest groundwater level, scenario 1.



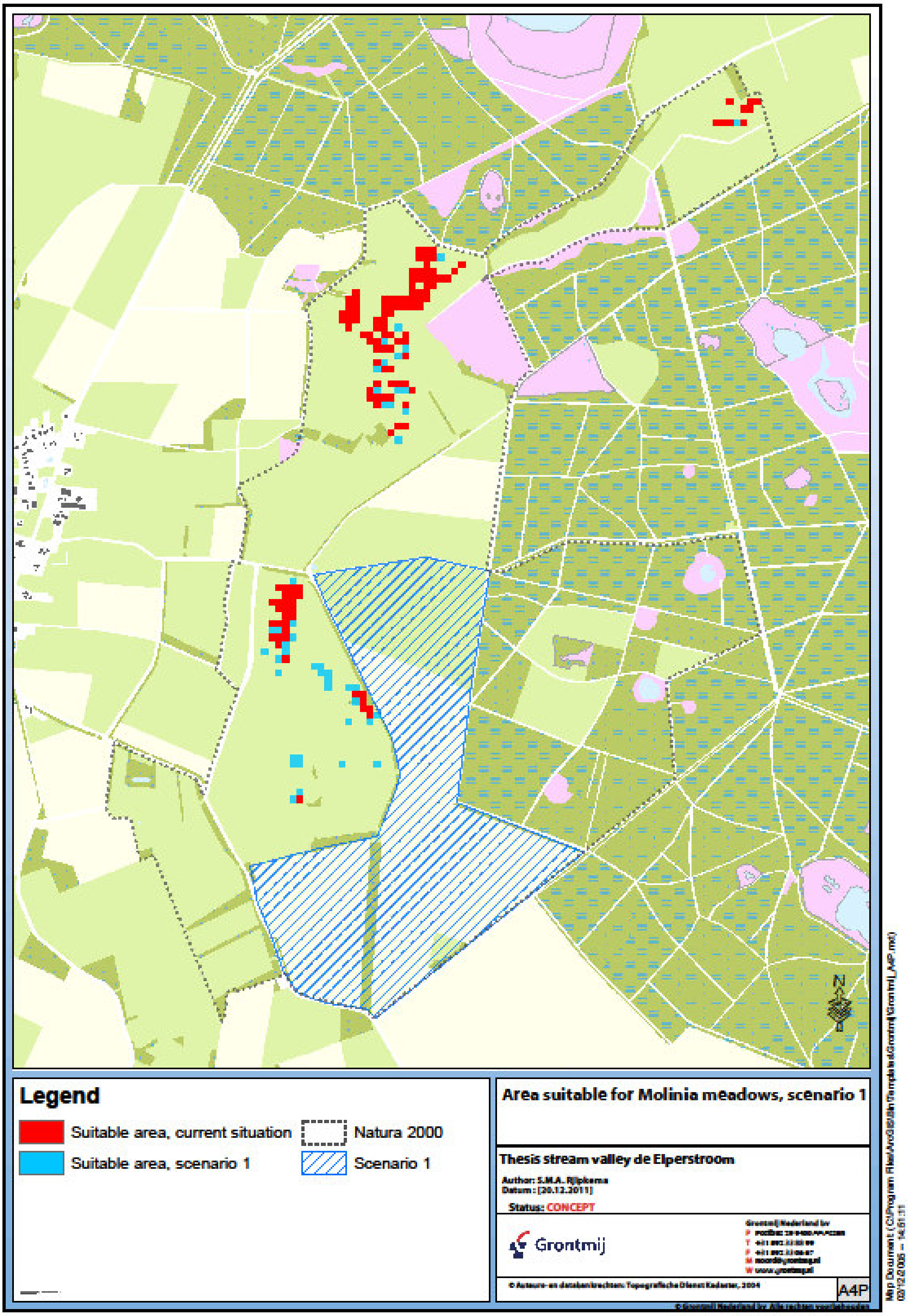
VI 18 Seepage to layer 1, scenario 1.



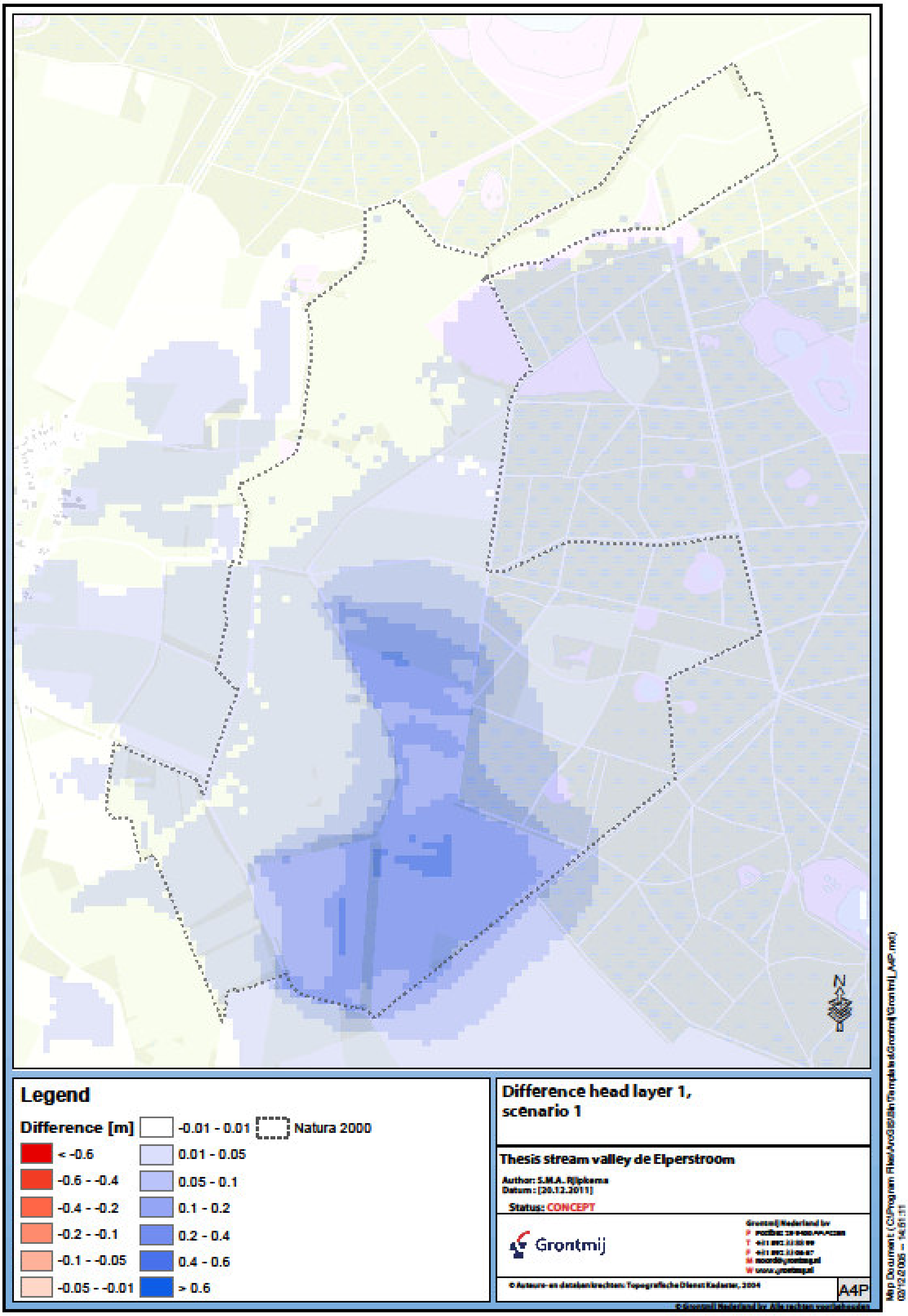
VI 19 Seepage to layer 3, scenario 1.



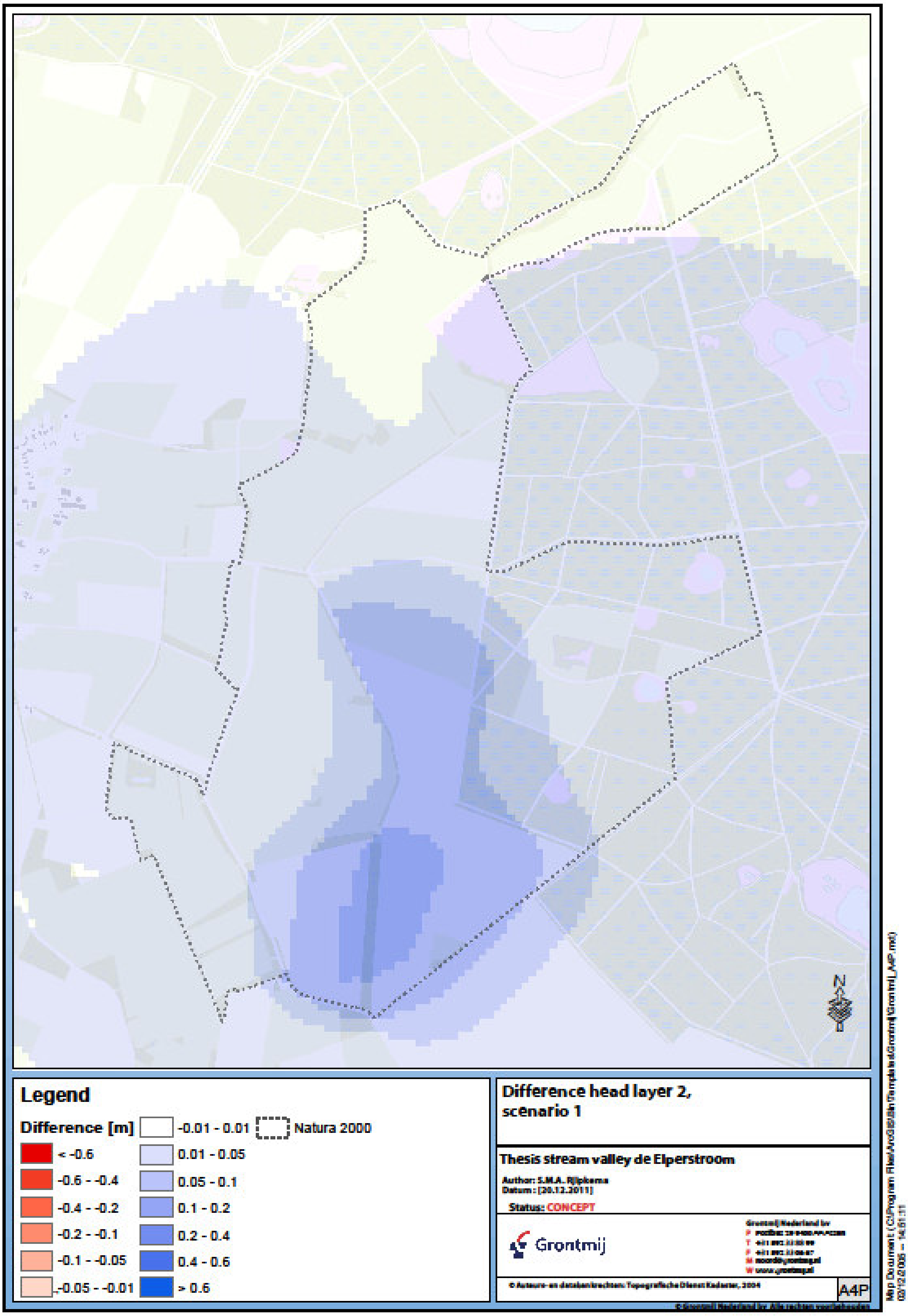
VI 20 Suitable area alkaline fens, scenario 1.



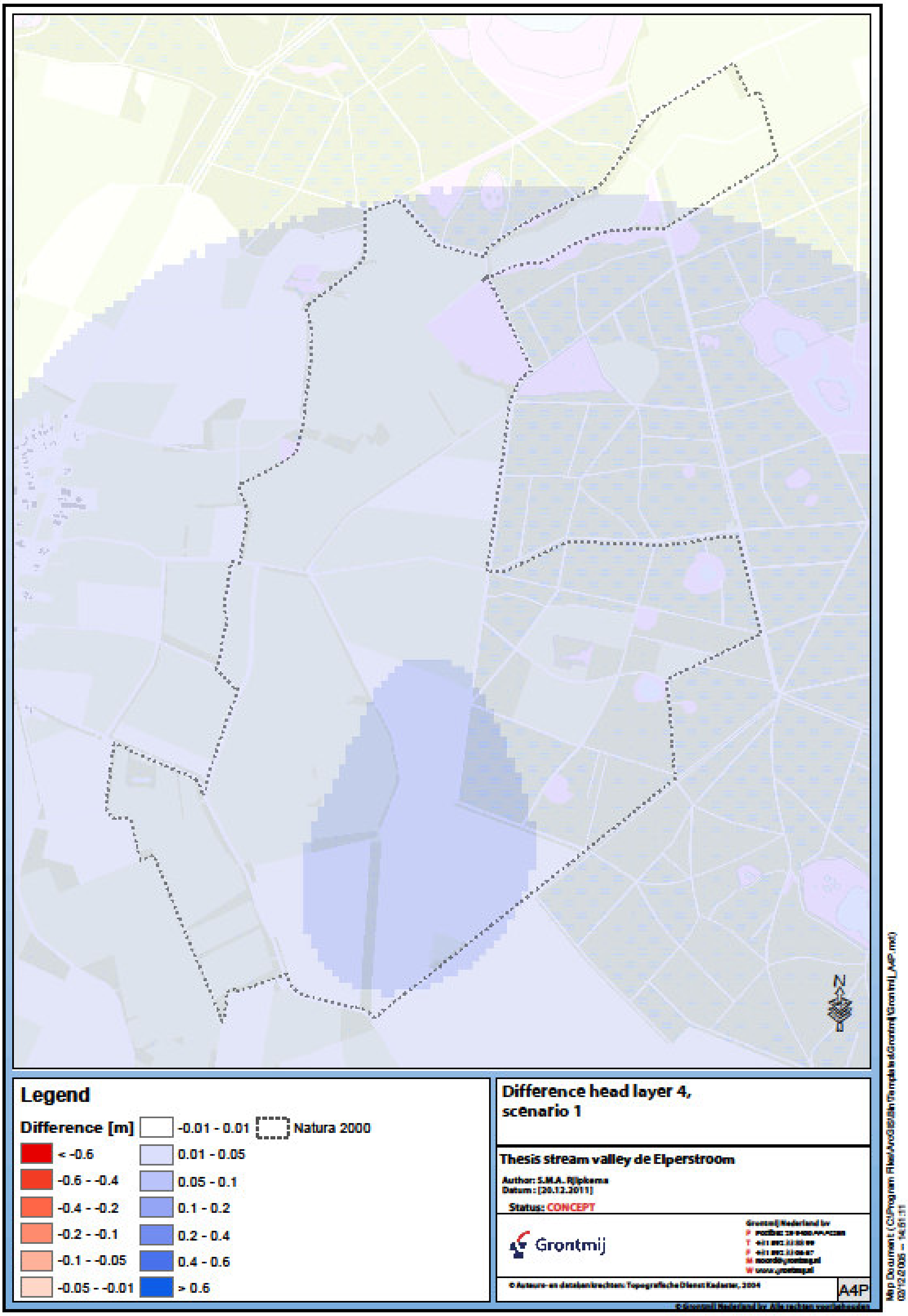
VI 21 Suitable area Molinia meadows, scenario 1.



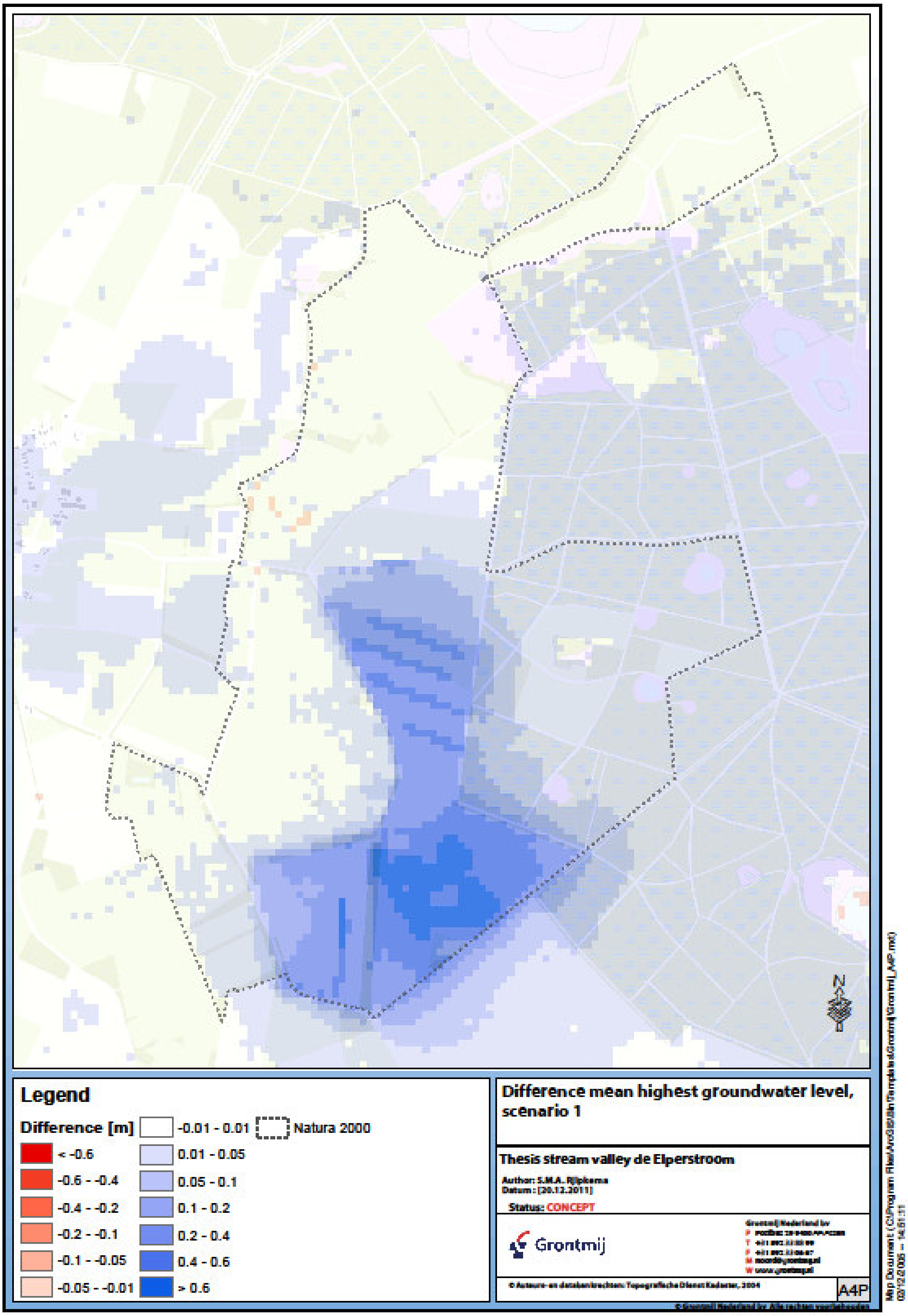
VI 22 Difference head layer 1, scenario 1.



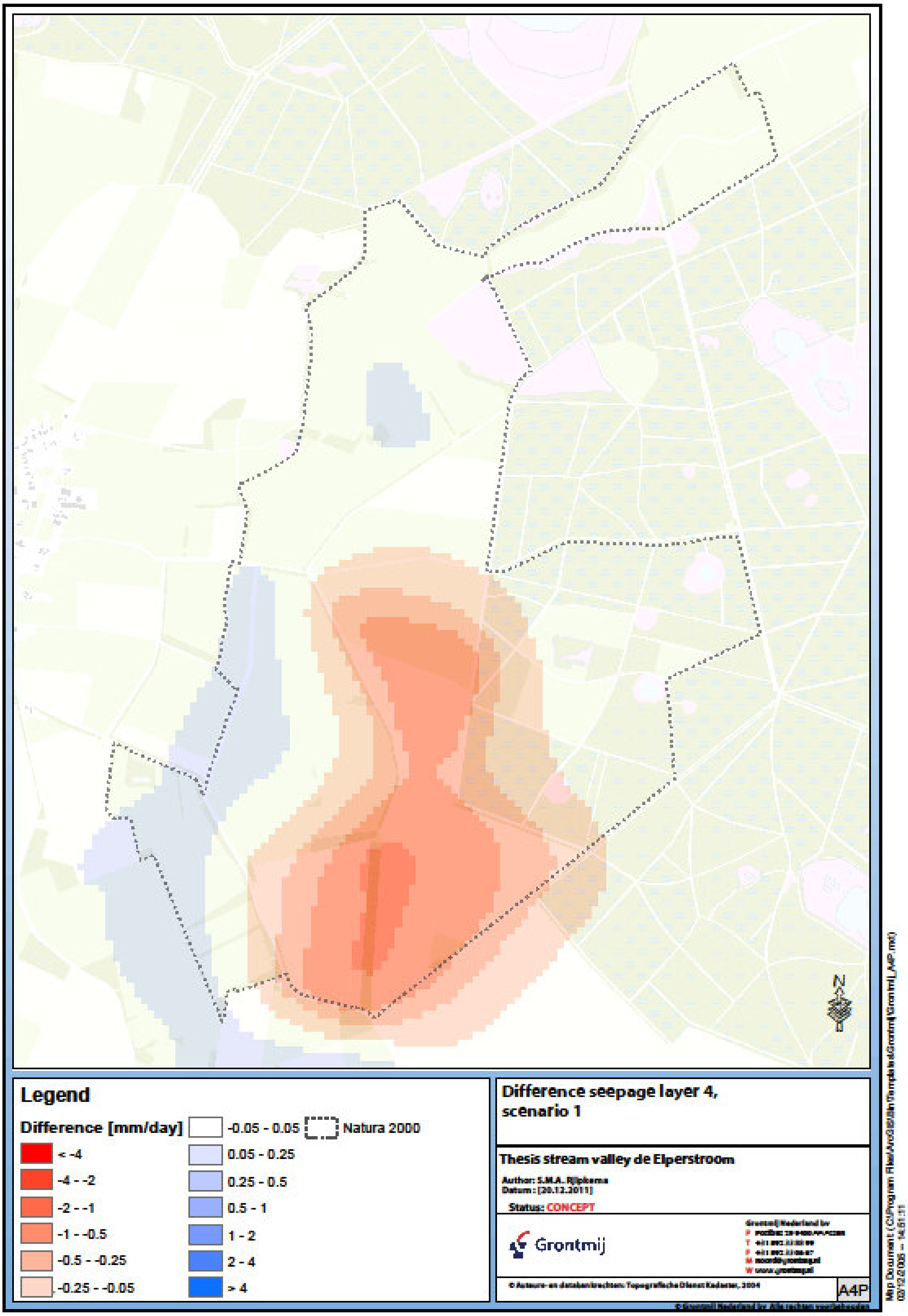
VI 23 Difference head layer 2, scenario 1.



VI 24 Difference head layer 4, scenario 1.



VI 25 Difference mean highest groundwater level, scenario 1.


N
Legend
Difference [mm/day]
🟥 < -4
🟥 -4 - -2
🟥 -2 - -1
🟥 -1 - -0.5
🟥 -0.5 - -0.25
🟥 -0.25 - -0.05
☐ -0.05 - 0.05
🟦 0.05 - 0.25
🟦 0.25 - 0.5
🟦 0.5 - 1
🟦 1 - 2
🟦 2 - 4
🟦 > 4
Natura 2000
Difference seepage layer 4, scenario 1
Thesis stream valley de Elperstroom
Author: S.M.A. Rijpkema
Datum : [20.12.2011]
Status: CONCEPT
Grontmij
Grontmij Nederland bv
© Auteurs- en databankrechten: Topografische Dienst Kadaster, 2004
A4P
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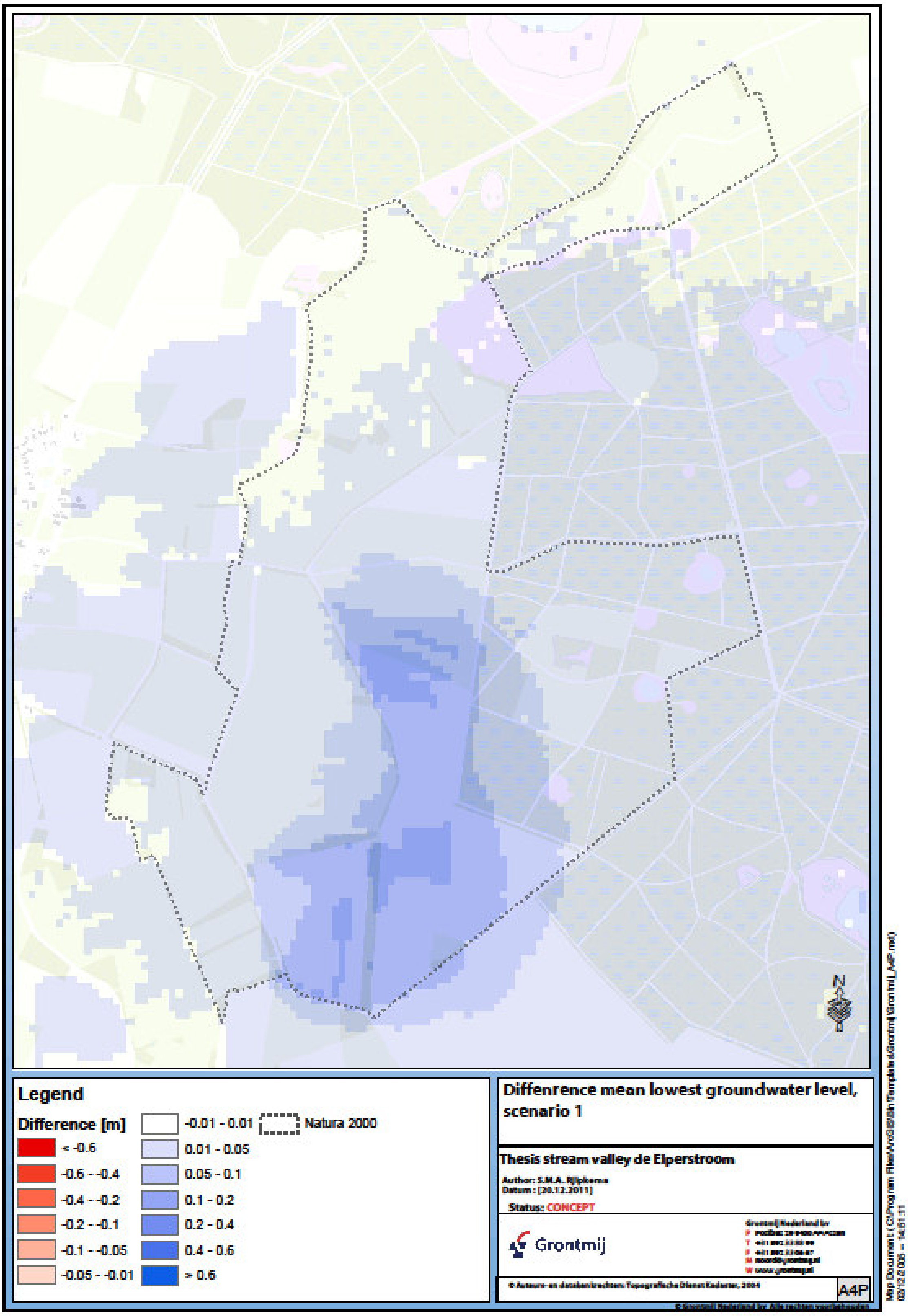
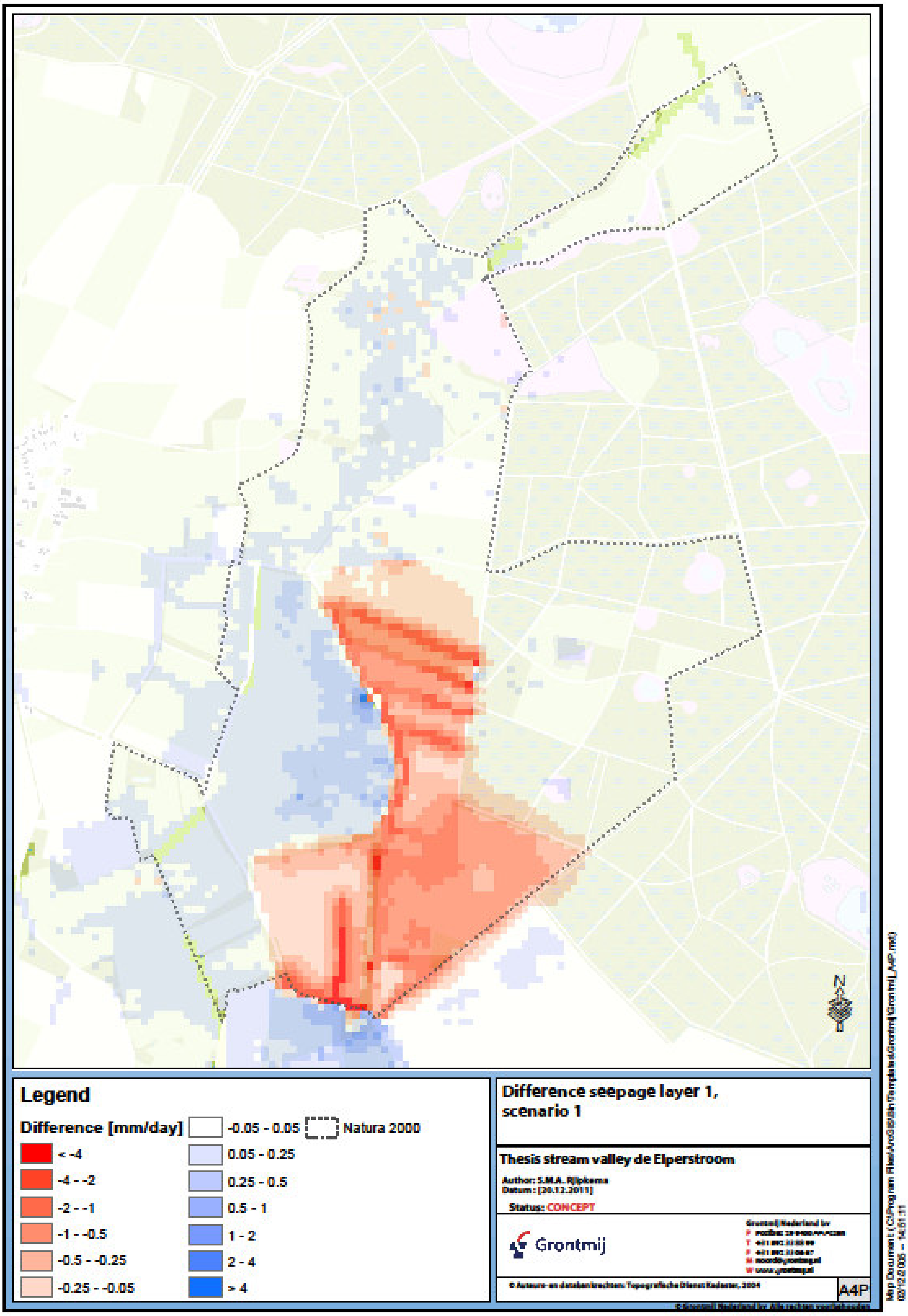
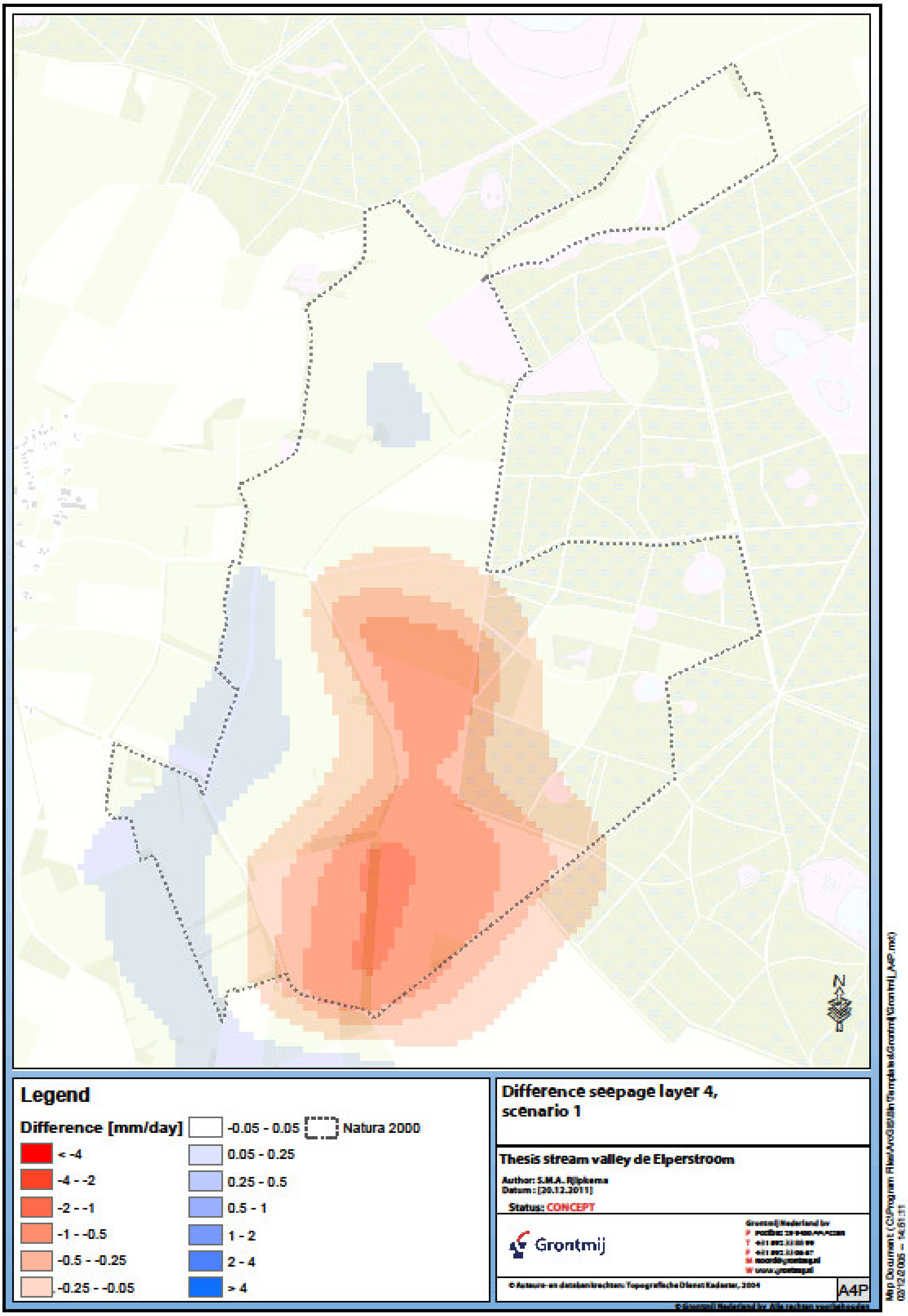
Map Document: (C:\Program Files\ArcGIS\Bin\Templates\Grontmij\Grontmij_A4P.mxd)
02/12/2005 -- 14:51:11



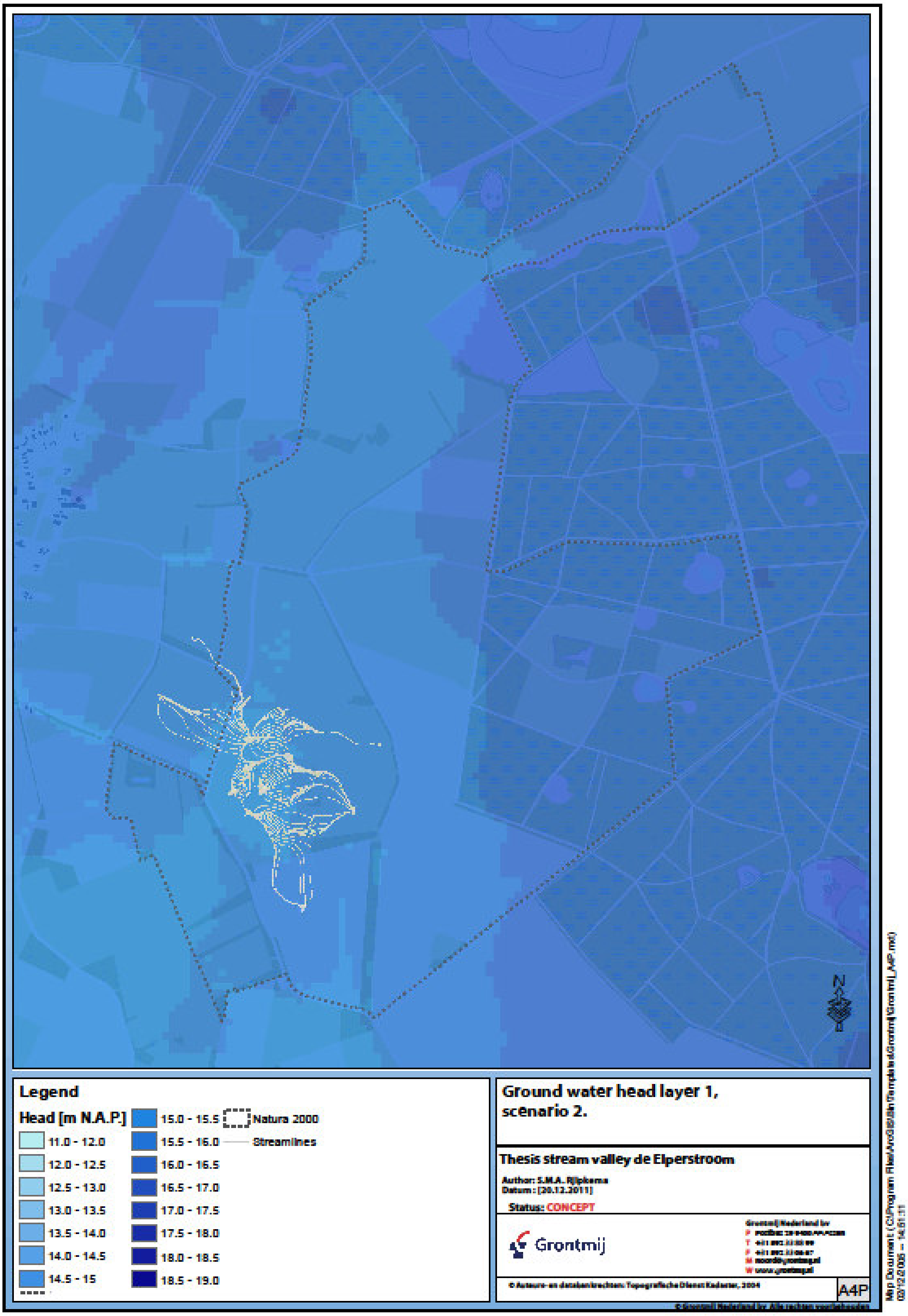
VI 26 Difference mean lowest groundwater level, scenario 1.



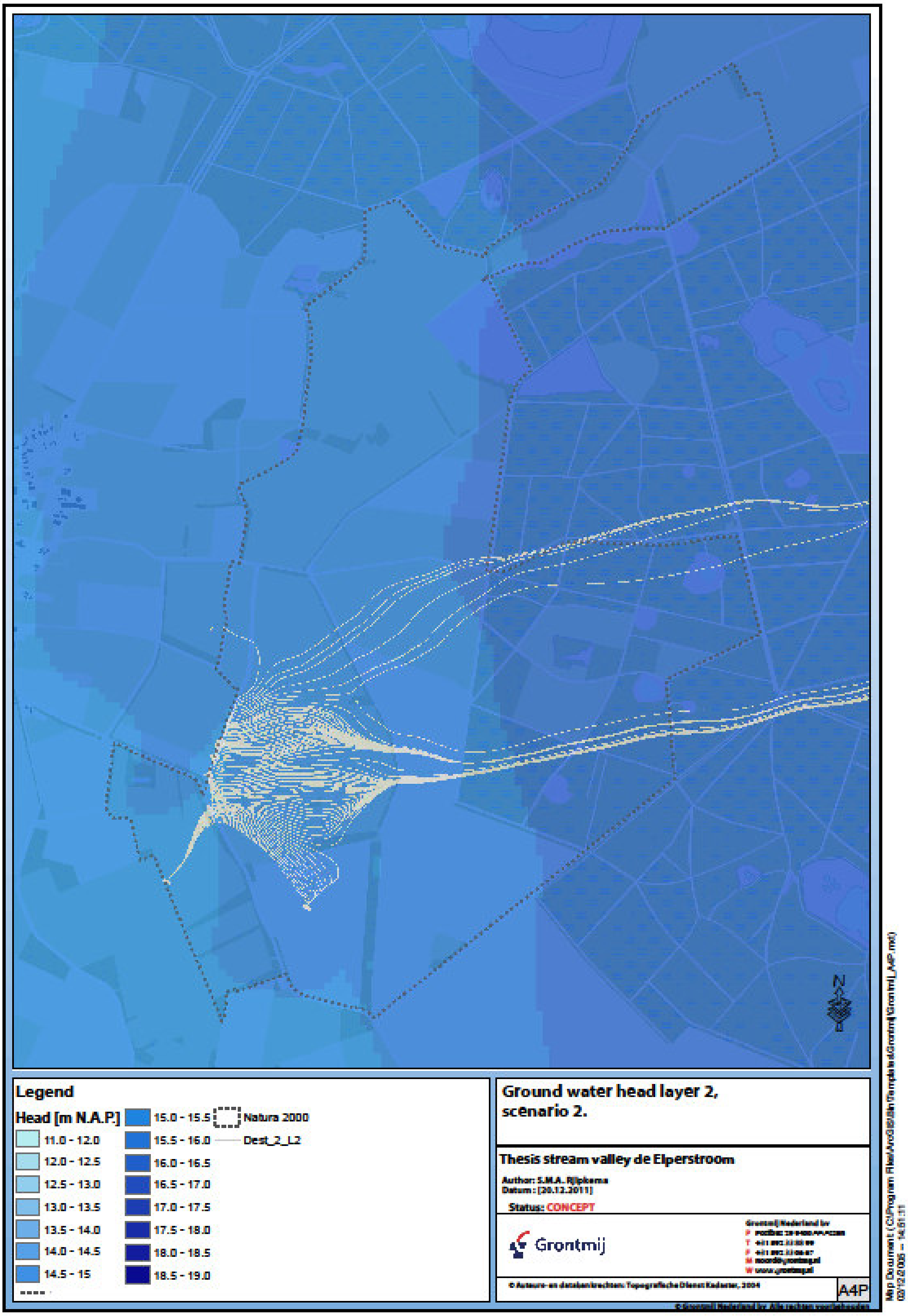
VI 27 Difference seepage, scenario 1.



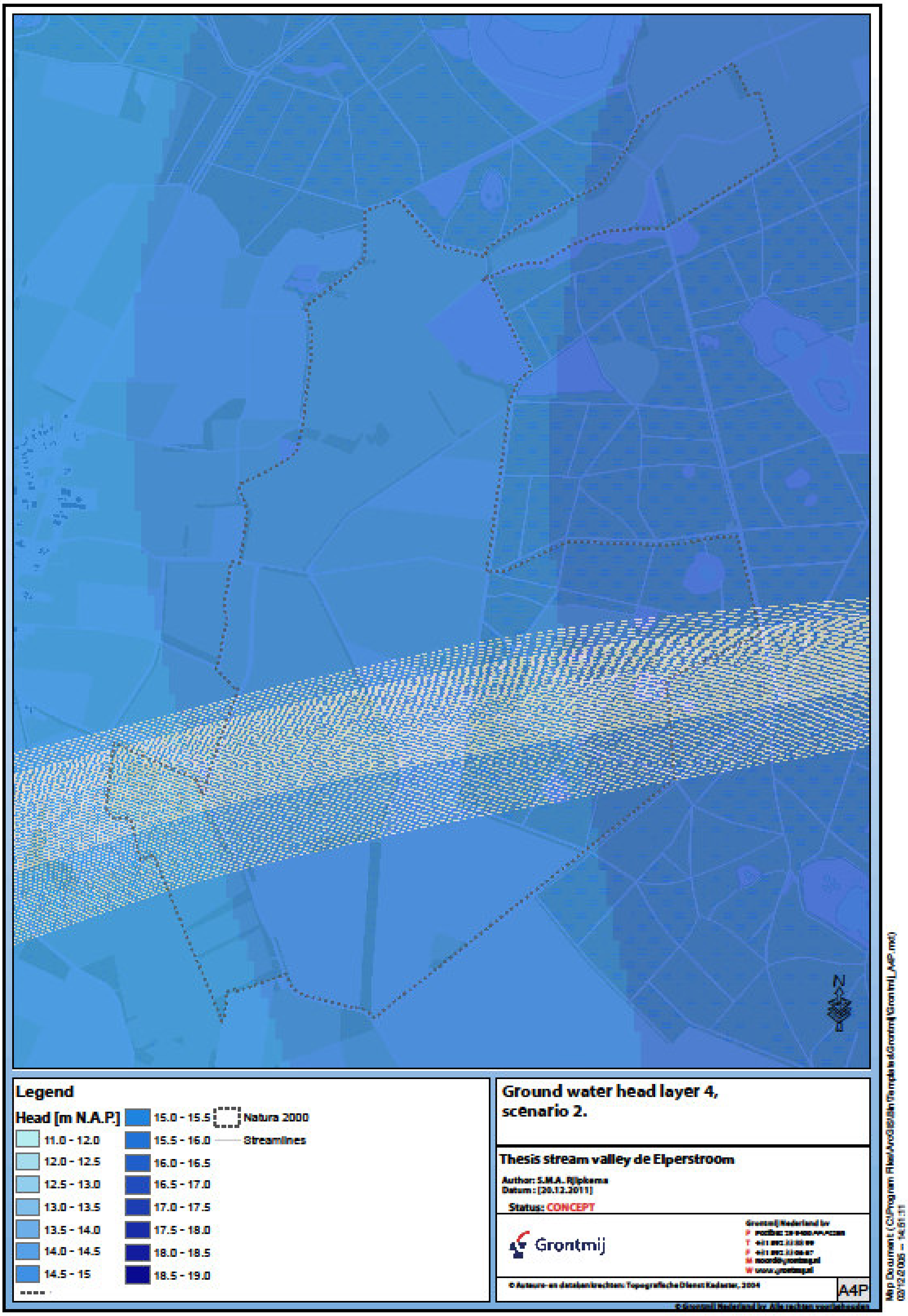
VI 28 Difference seepage layer 3, scenario 1.



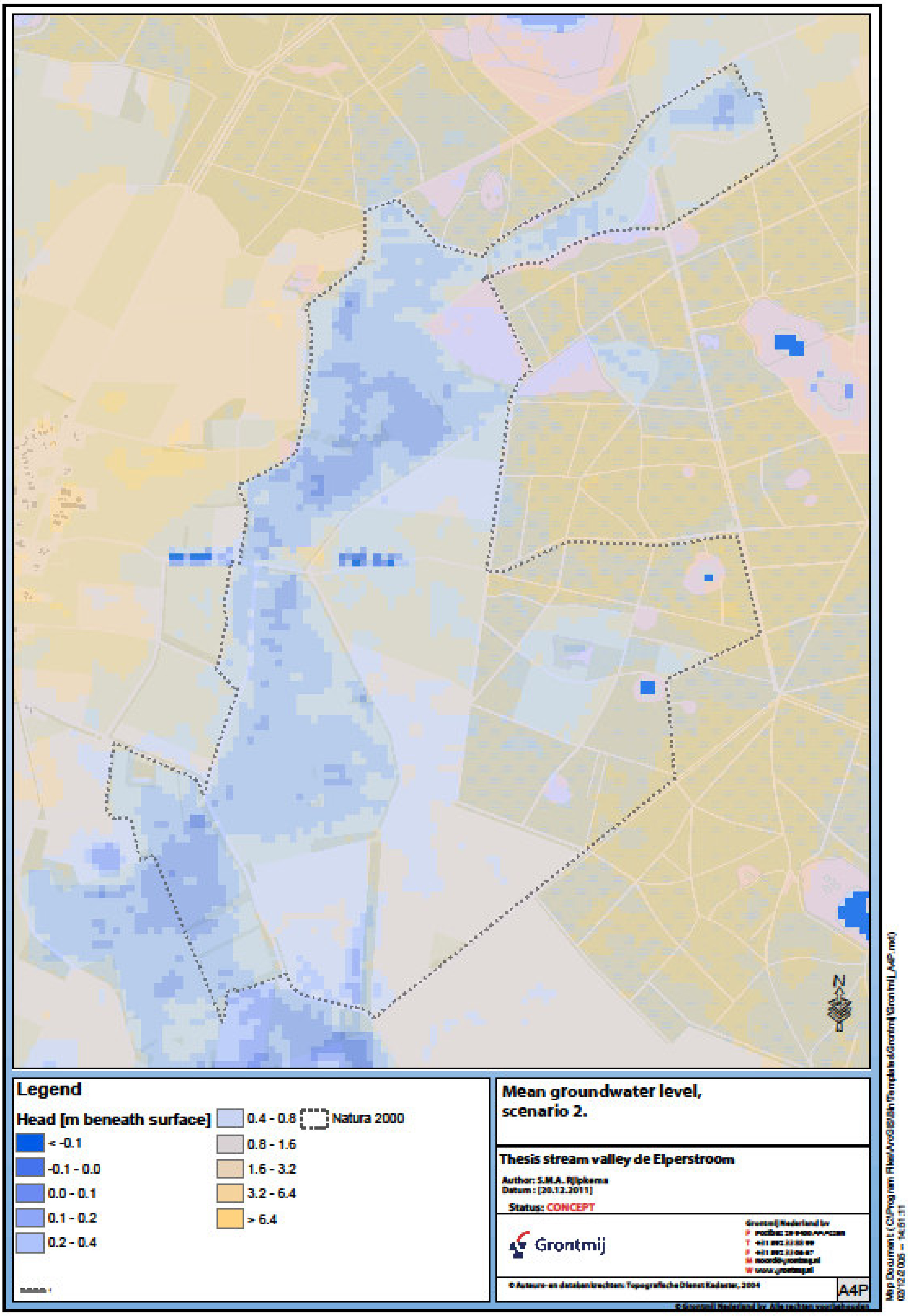
VI 29 Head layer 1, scenario 2.



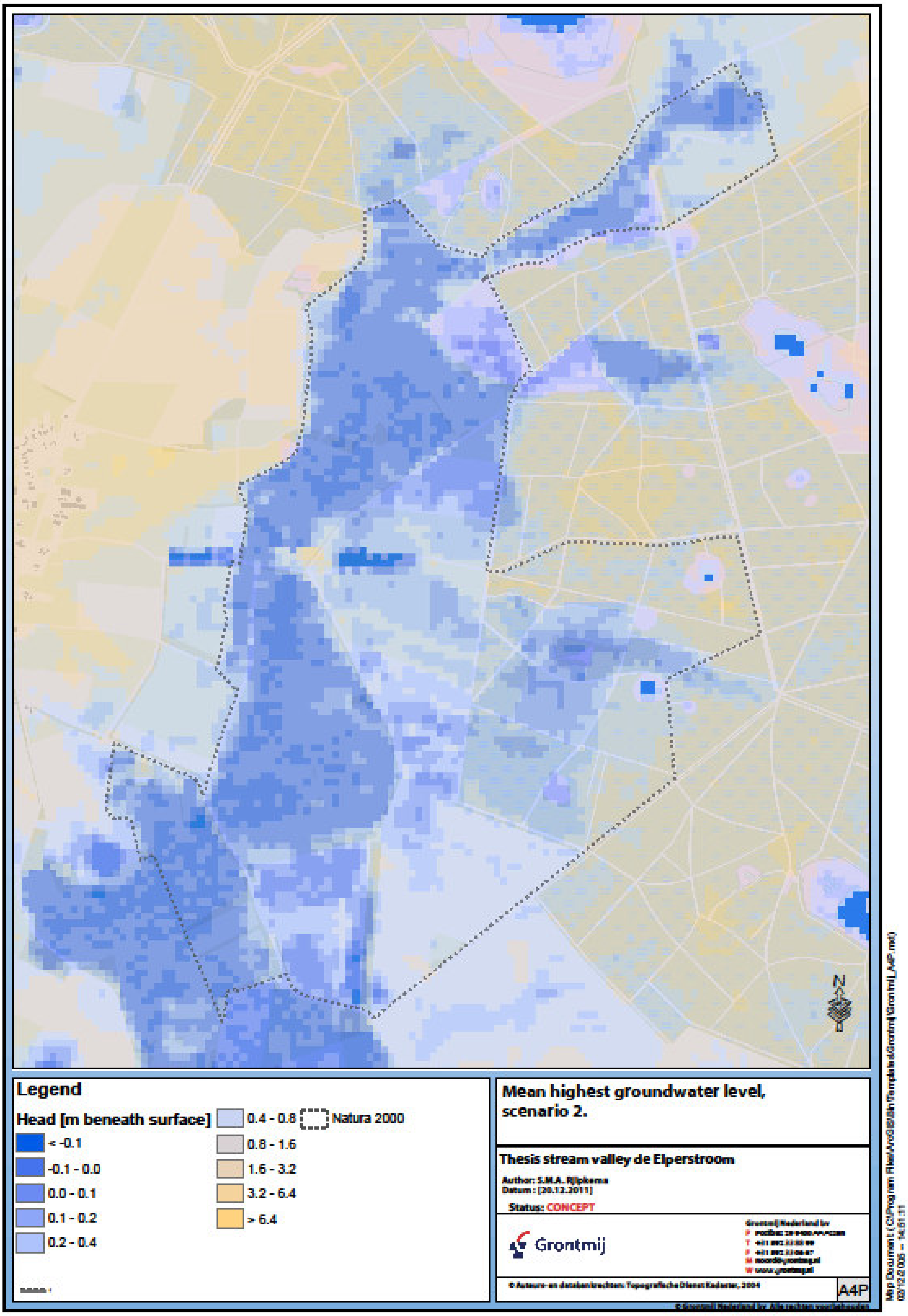
VI 30 Head layer 2, scenario 2.



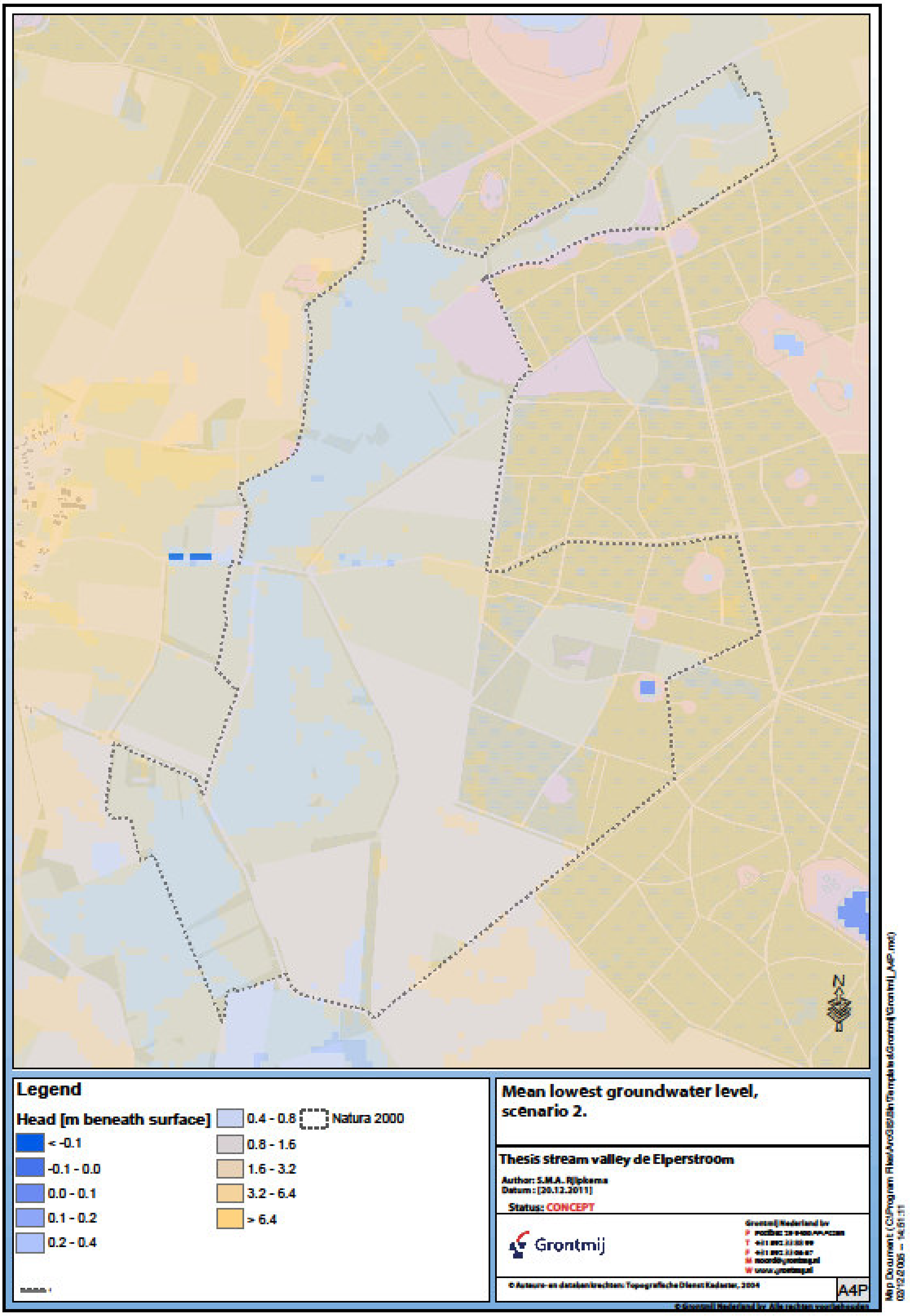
VI 31 Head layer4, scenario 2.



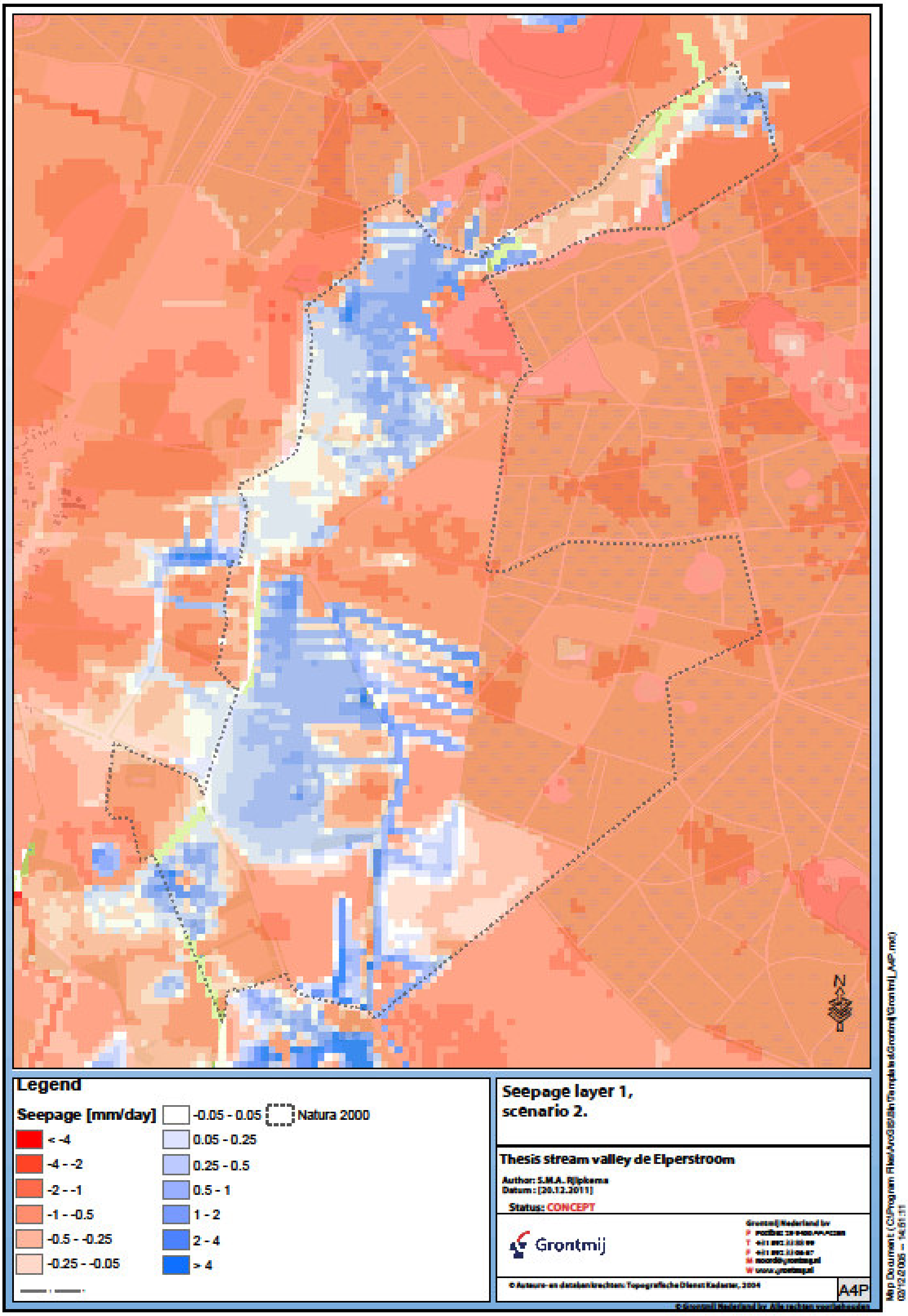
VI 32 Mean groundwater levels, scenario 2.



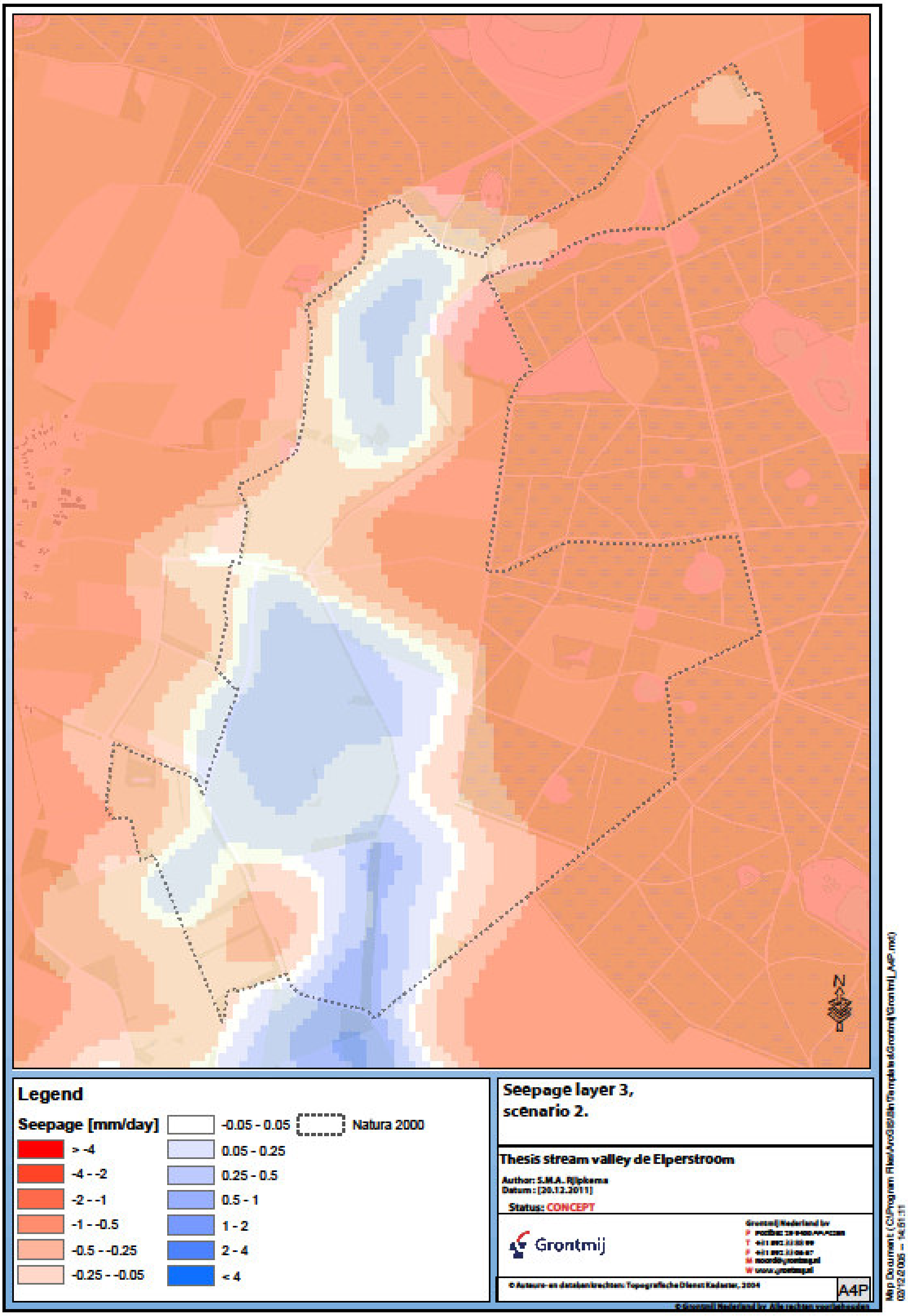
VI 33 Mean highest groundwater levels, scenario 2.



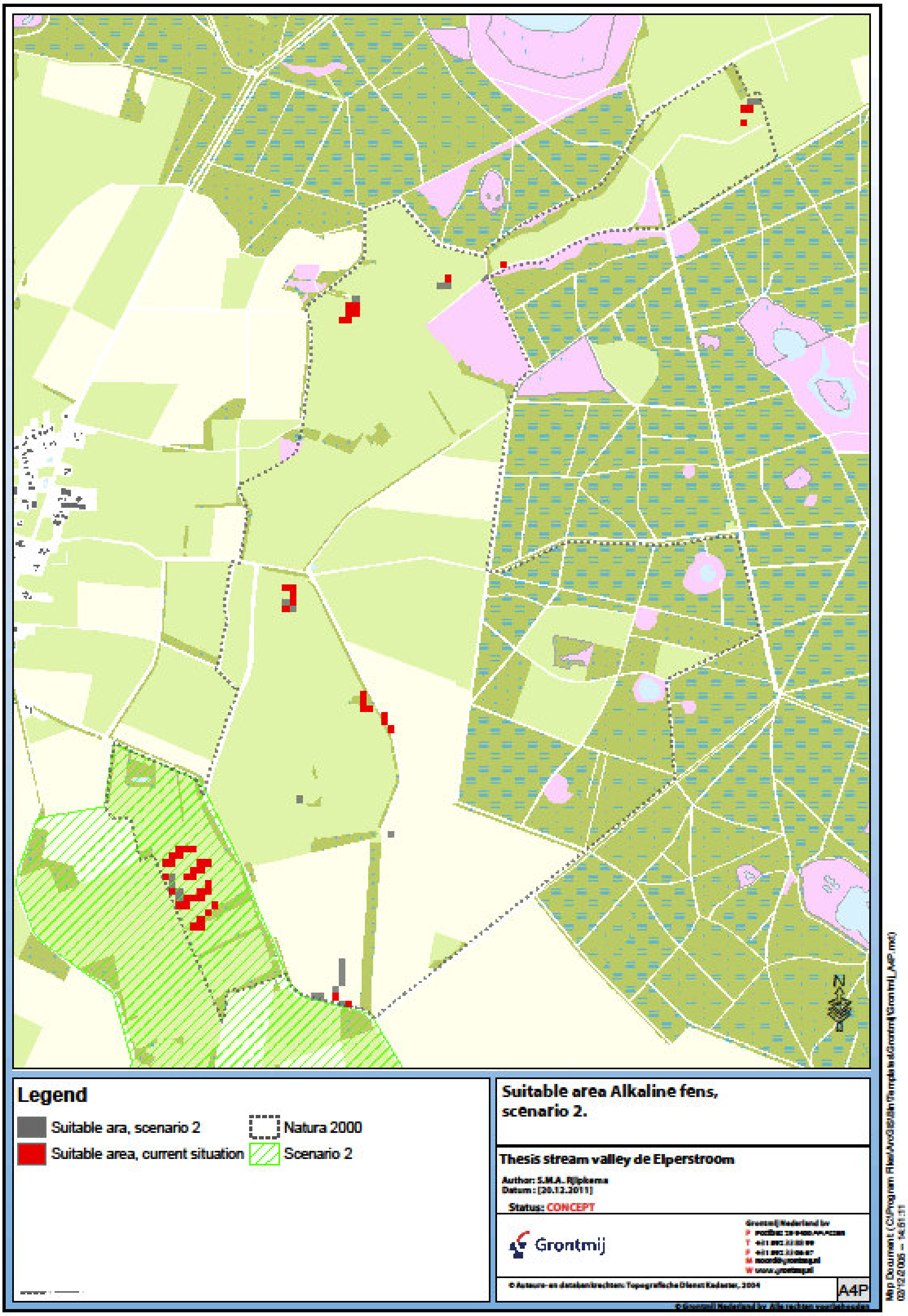
VI 34 Mean lowest groundwater levels, scenario 2.



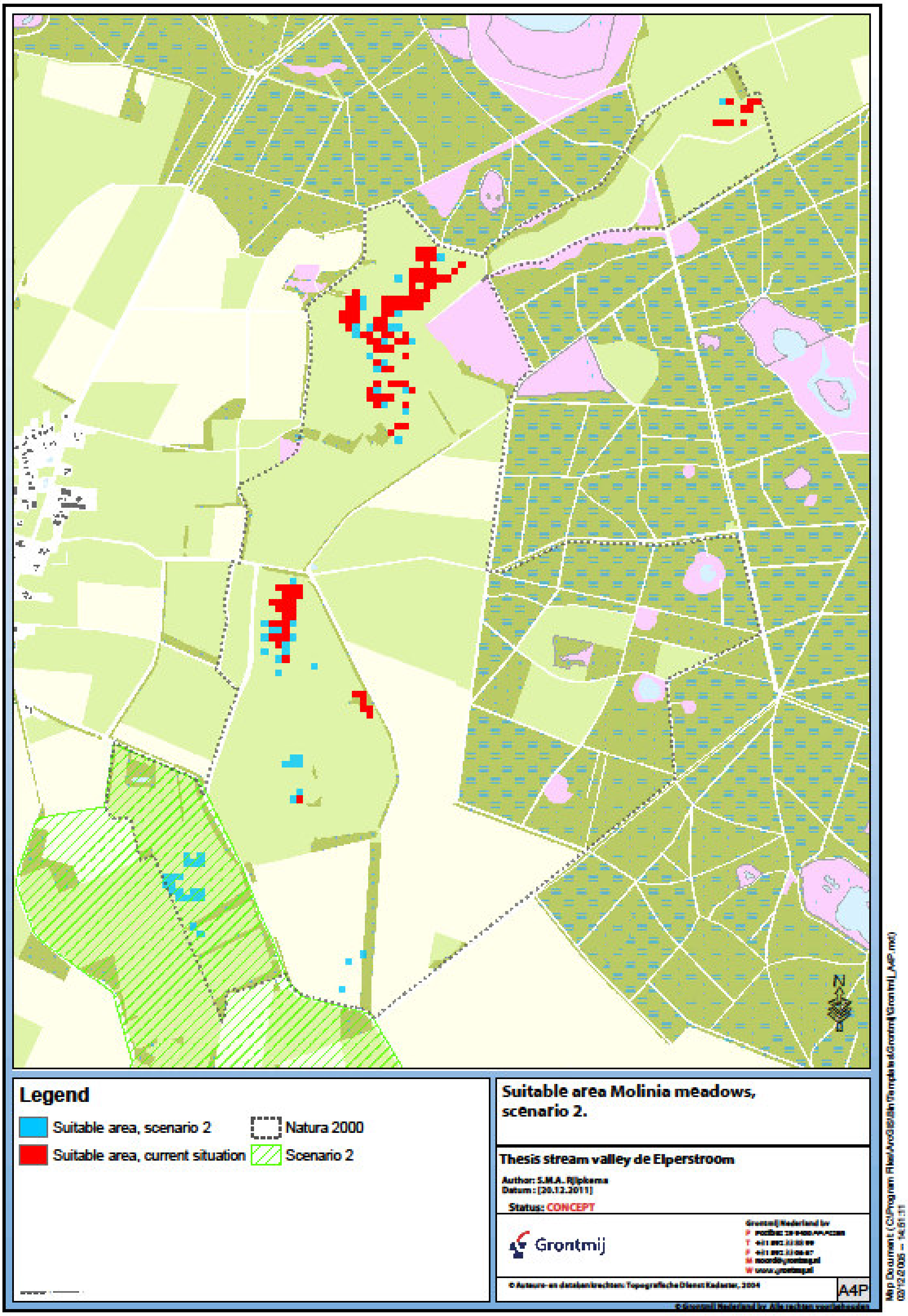
VI 35 Seepage to layer 1, scenario 2.



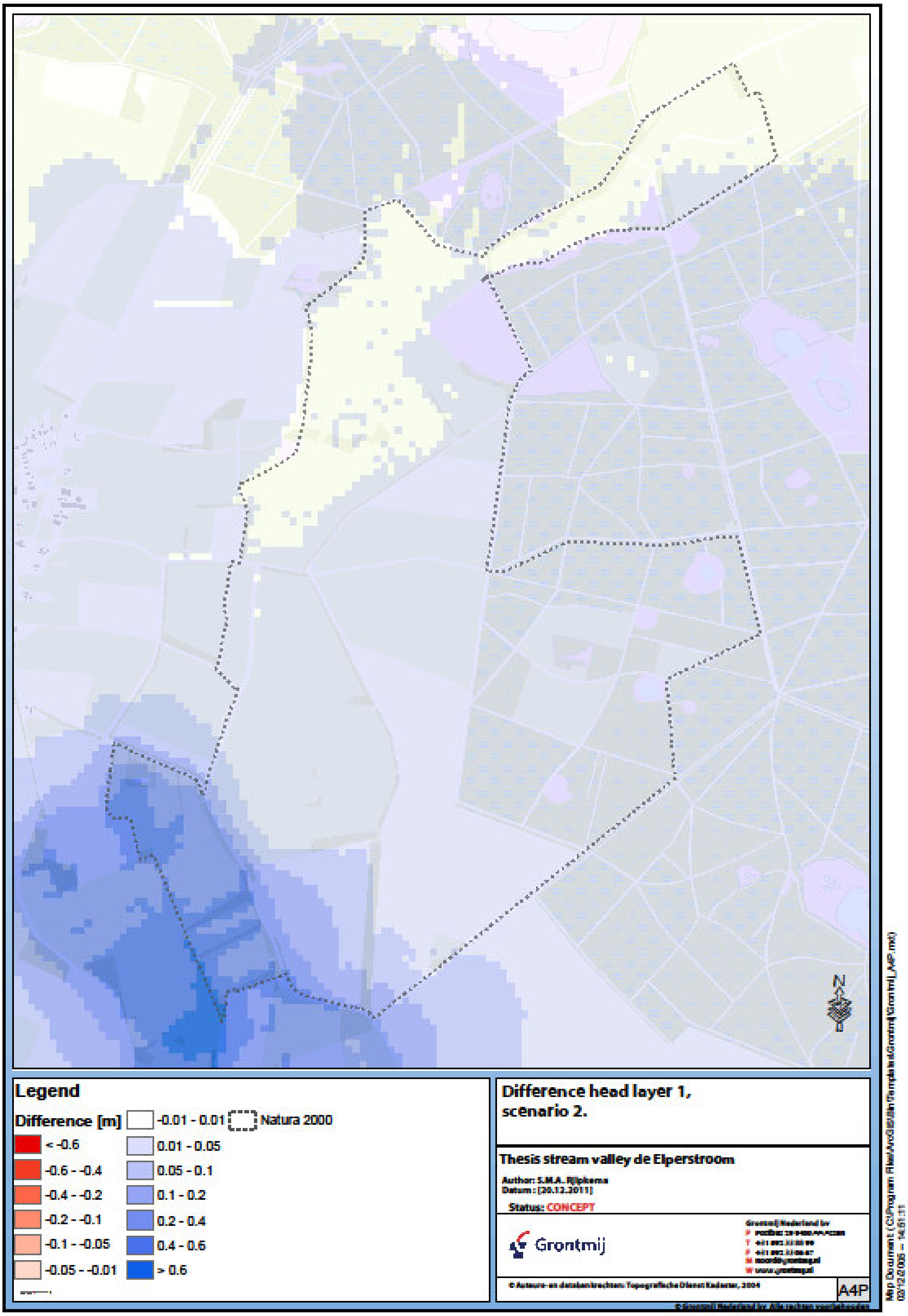
VI 36 Seepage to layer 3, scenario 2.



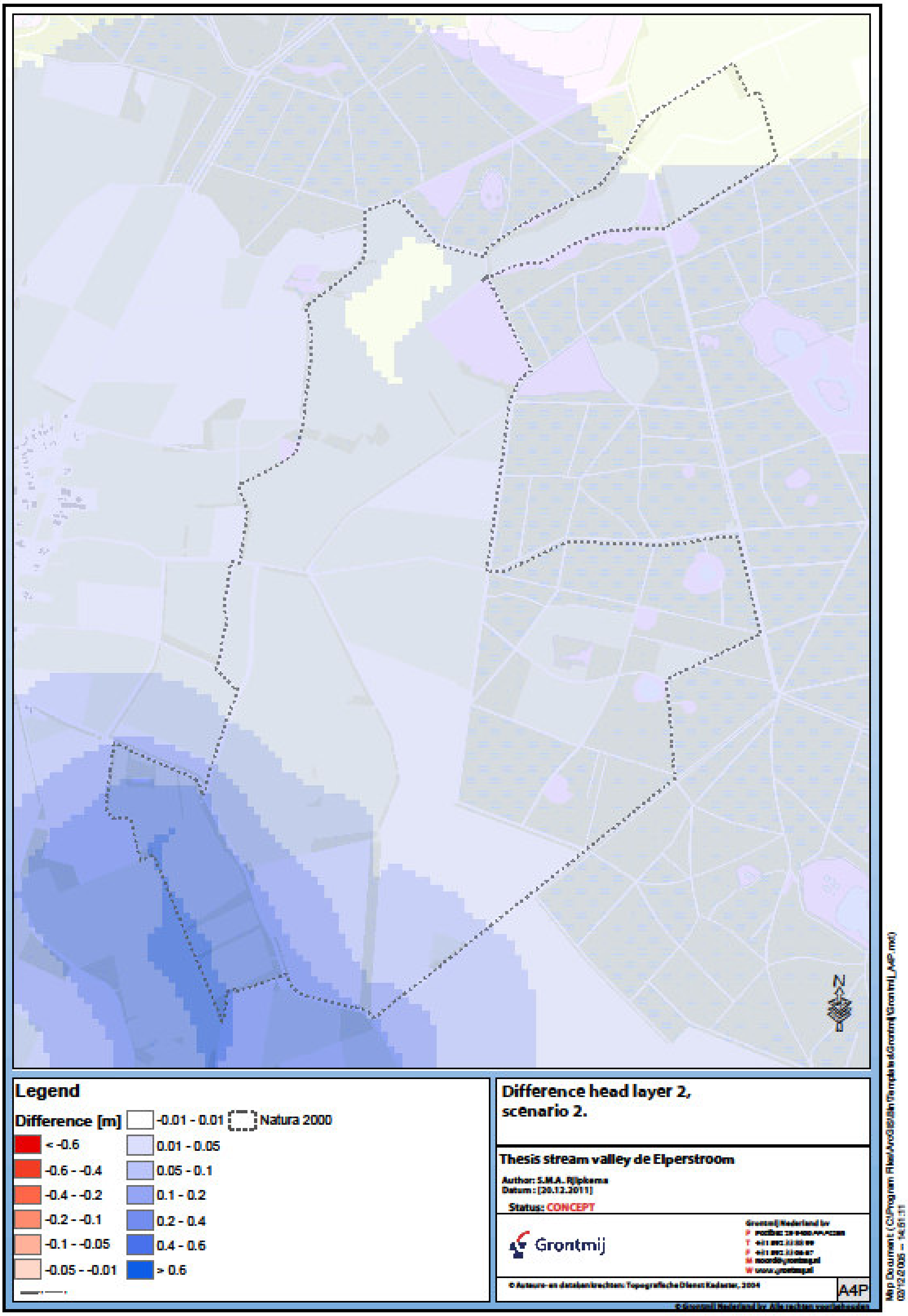
VI 37 Suitable area for alkaline fens, scenario 2.



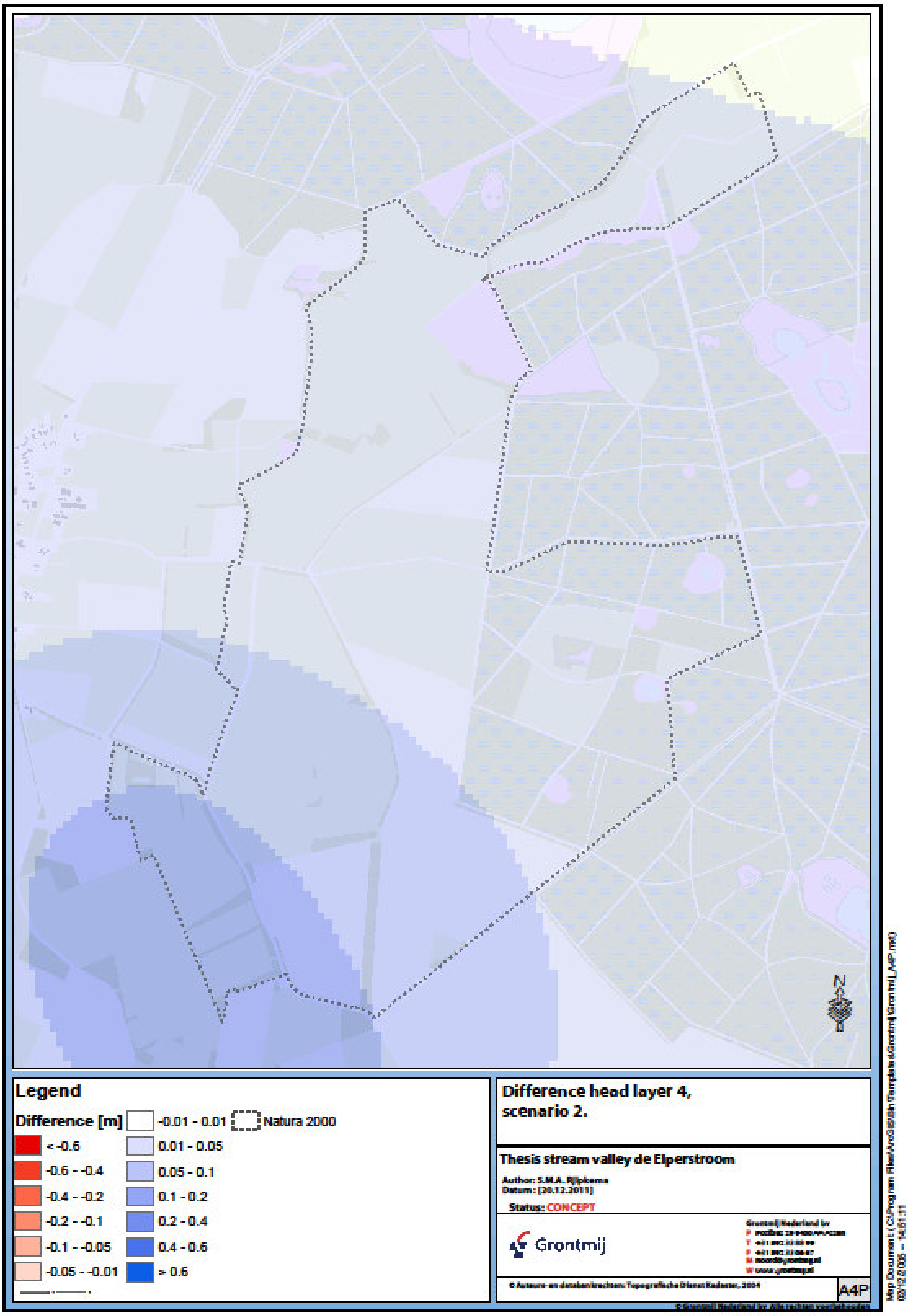
VI 38 Suitable area Molinia meadows, scenario 2.



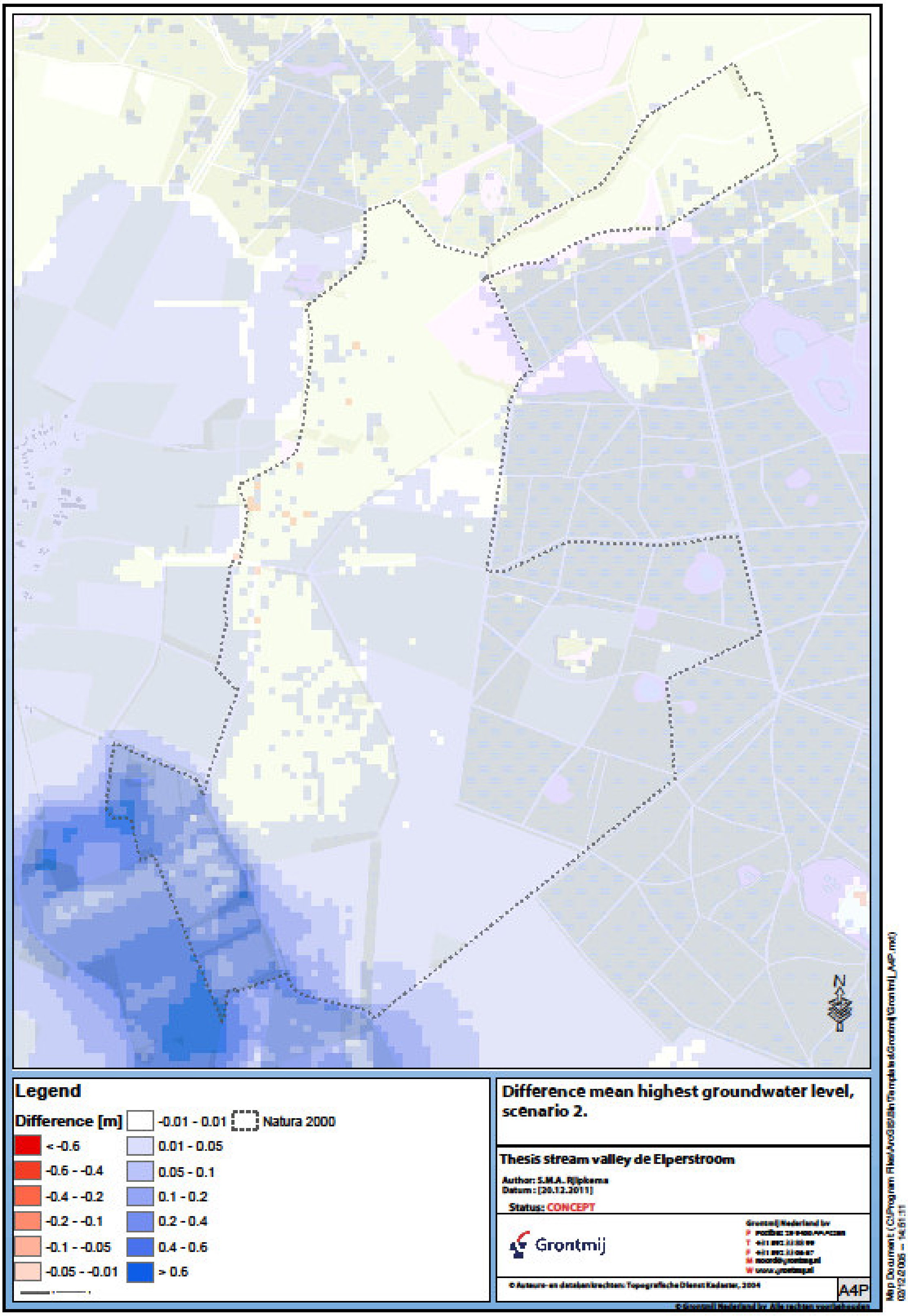
VI 39 Difference head layer 1, scenario 2.



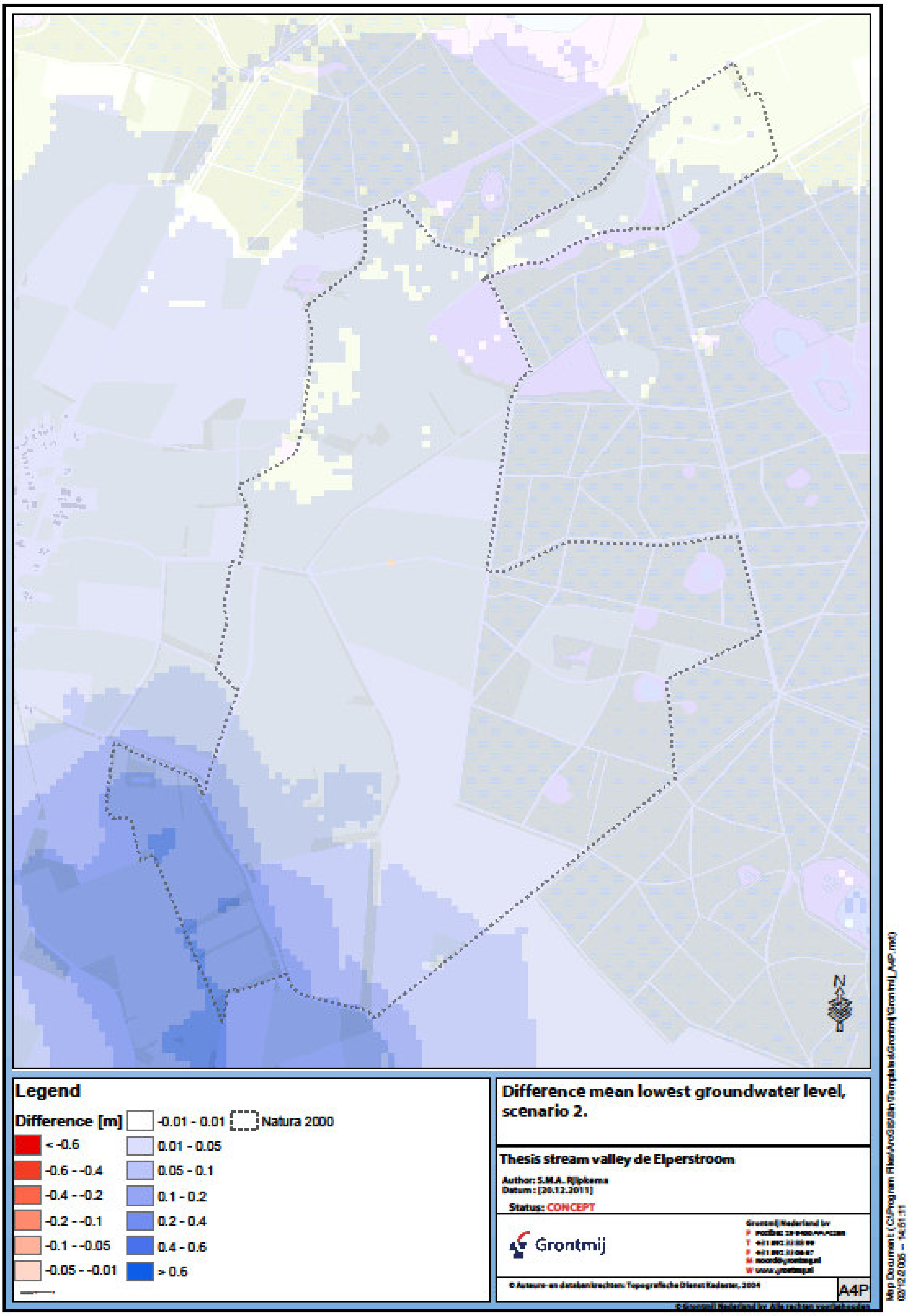
VI 40 Difference head layer 2, scenario 2.



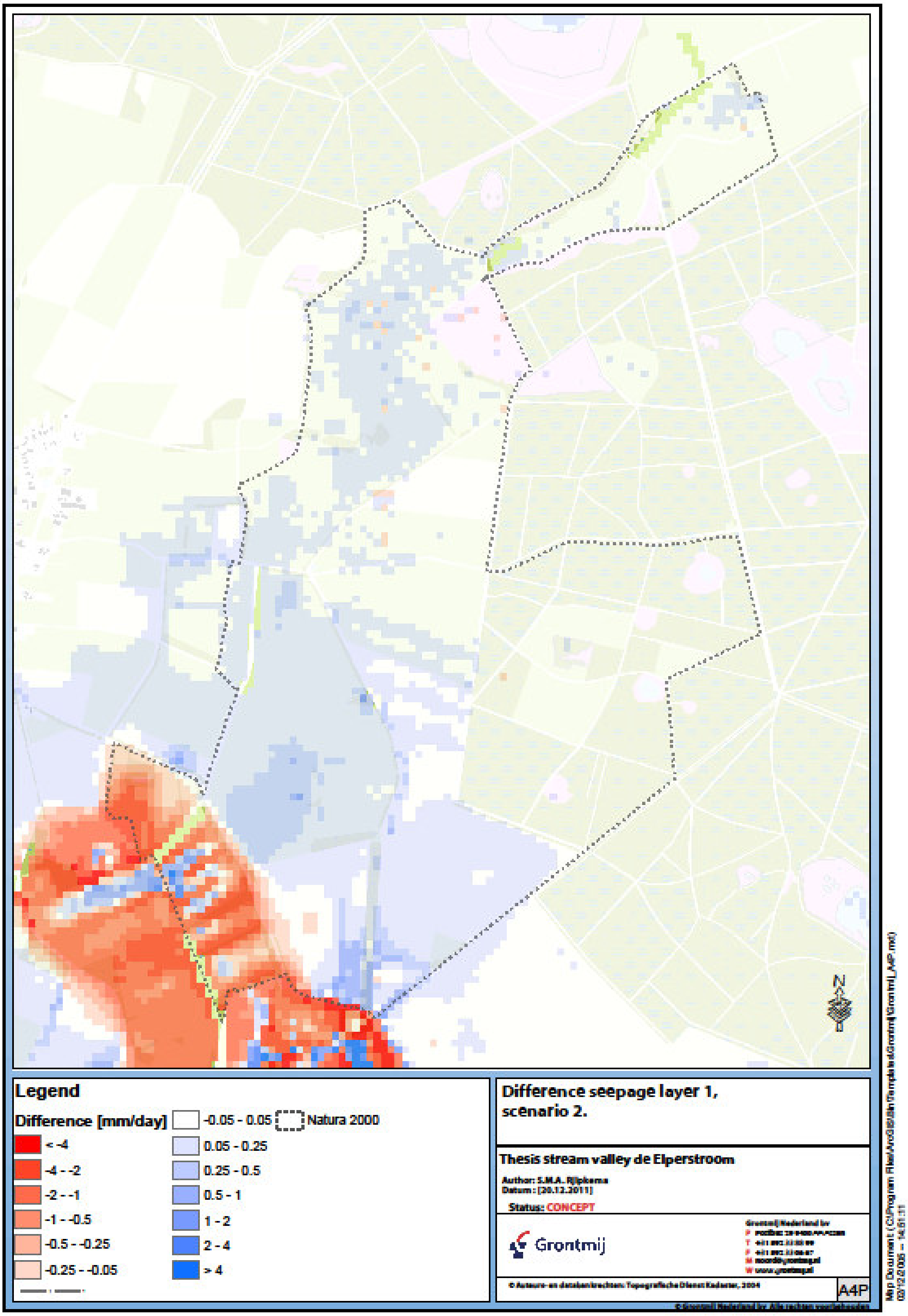
VI 41 Difference head layer 4, scenario 2.



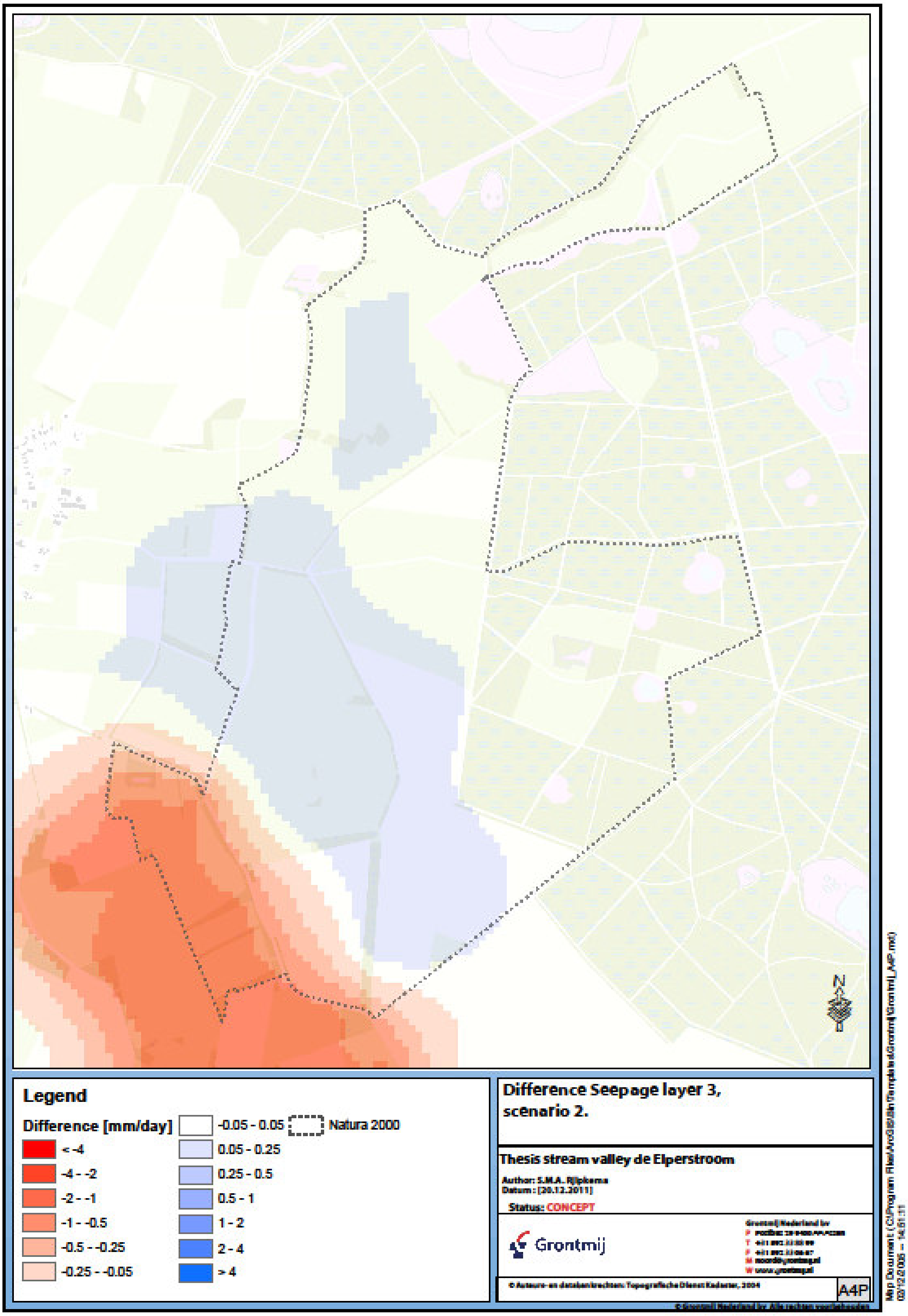
VI 42 Difference mean highest groundwater level, scenario 2.



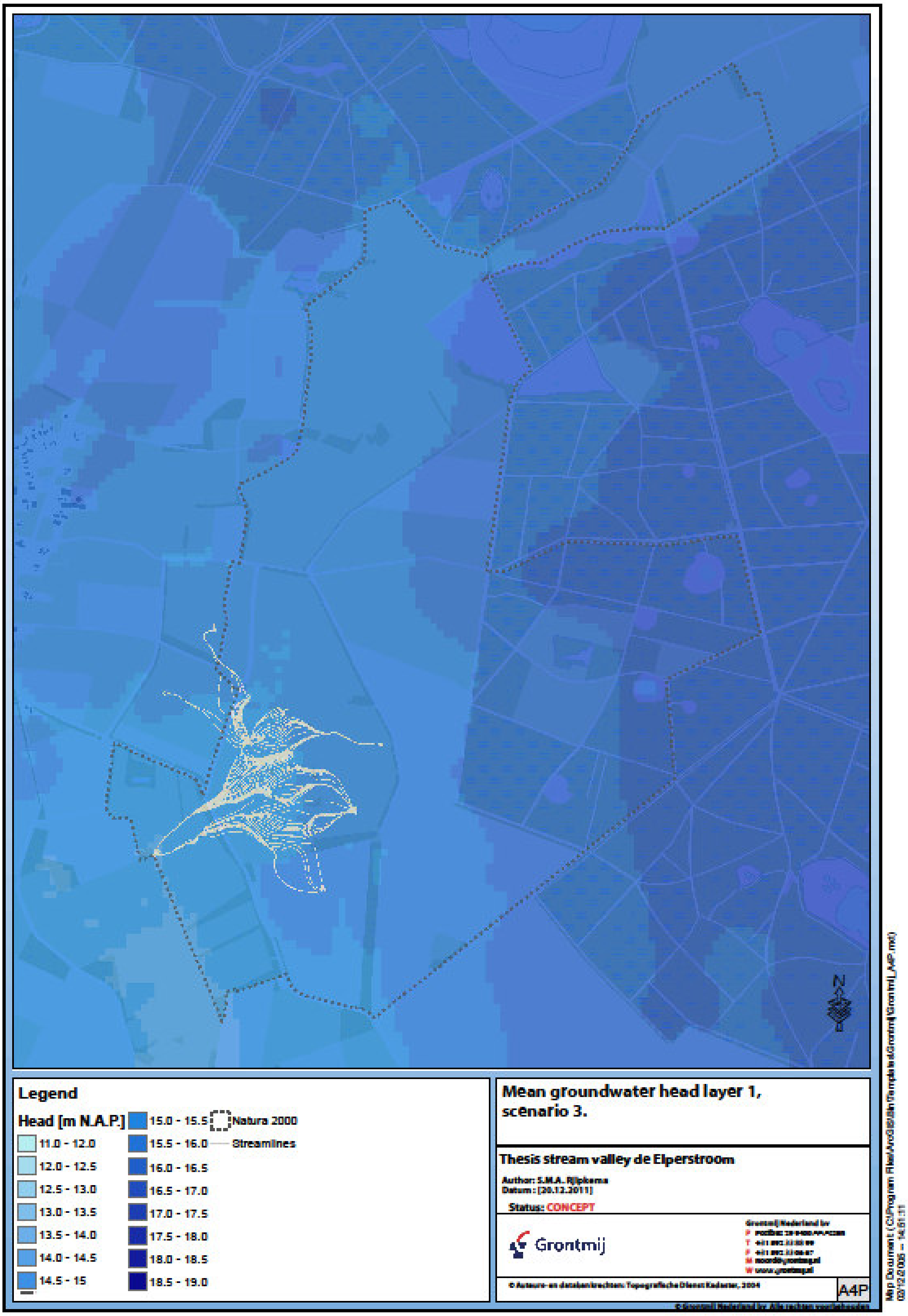
VI 43 Difference mean lowest groundwater level, scenario 2.



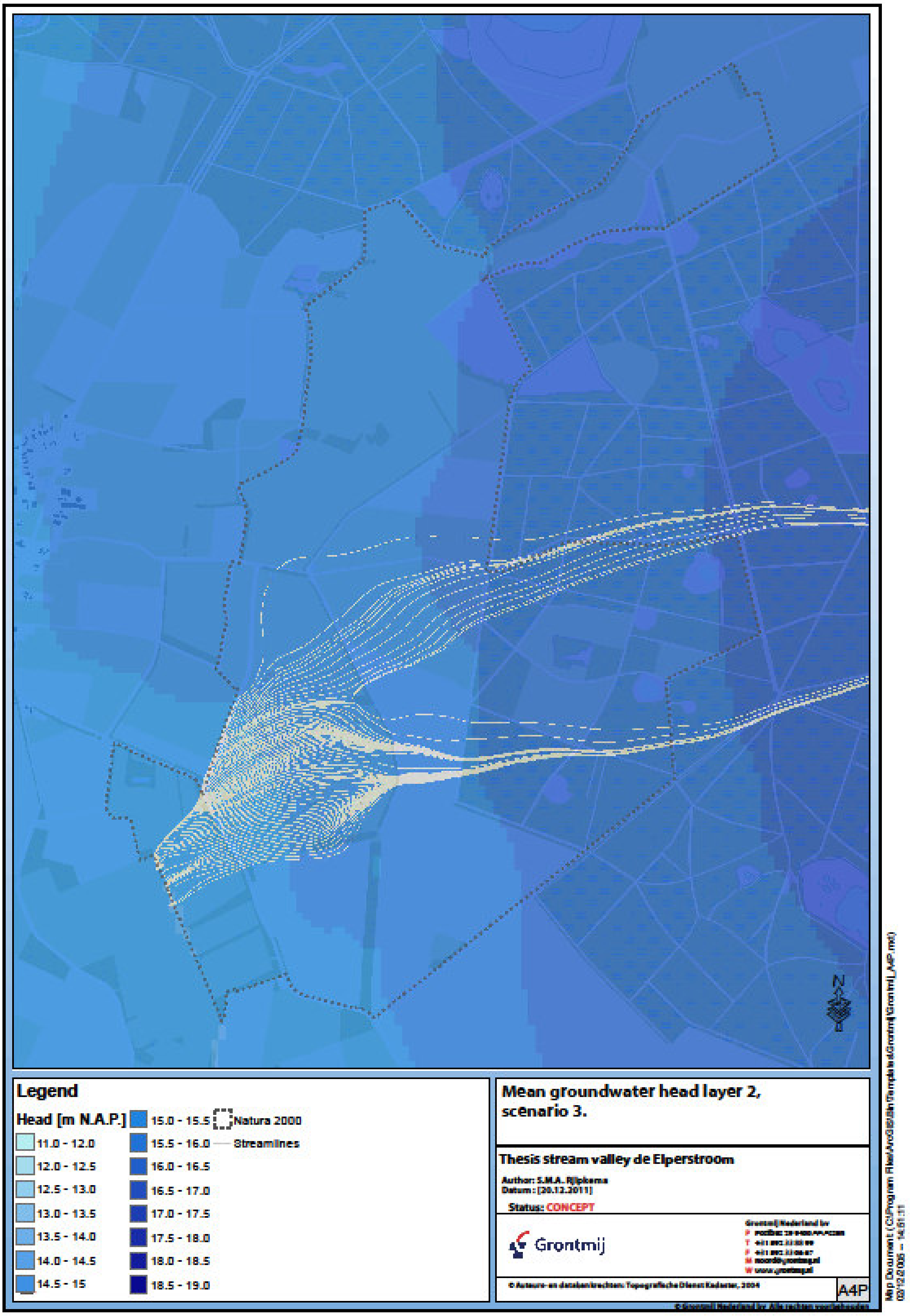
VI 44 Difference seepage layer 1, scenario 2.



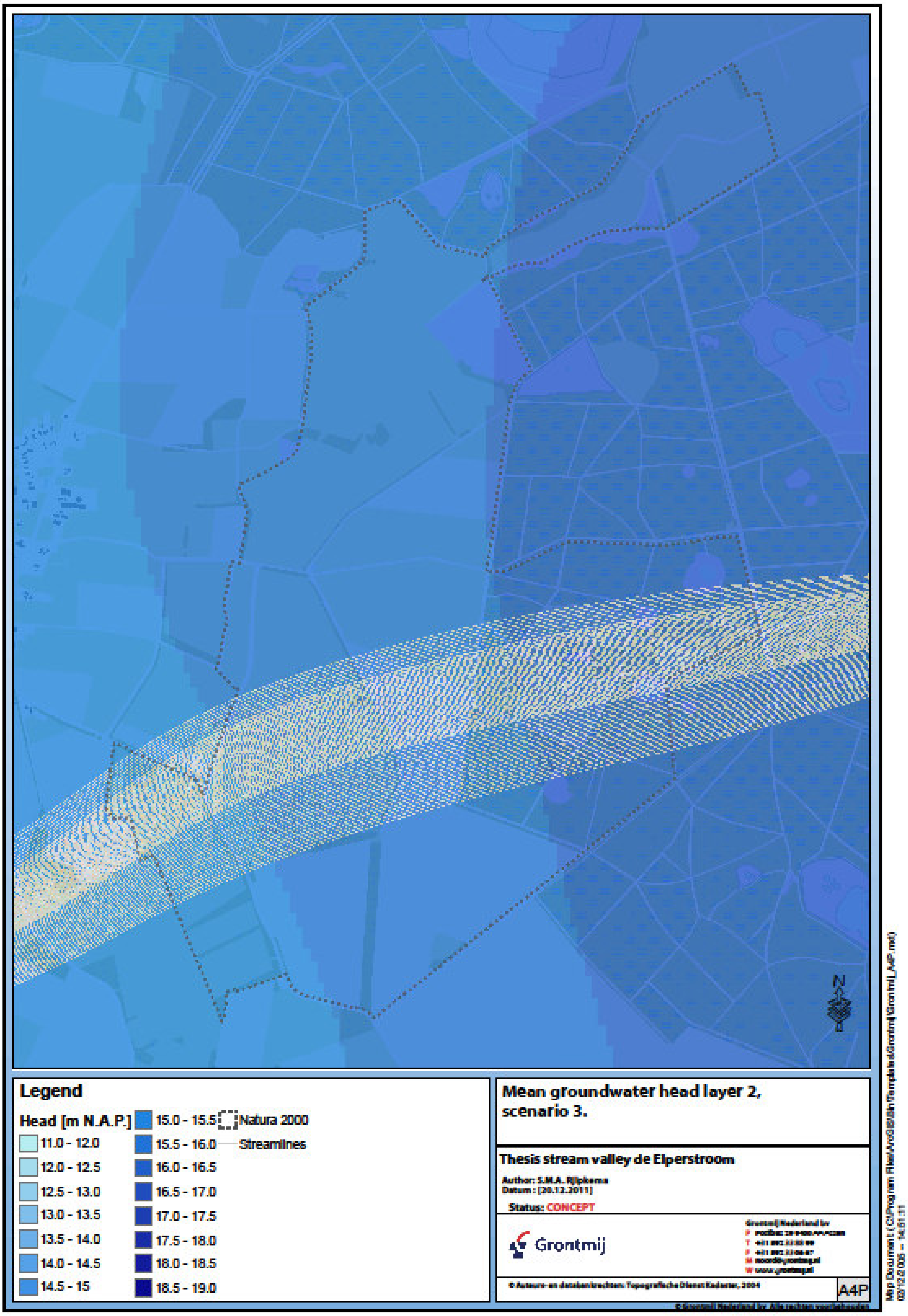
VI 45 Difference seepage layer 3, scenario 2.



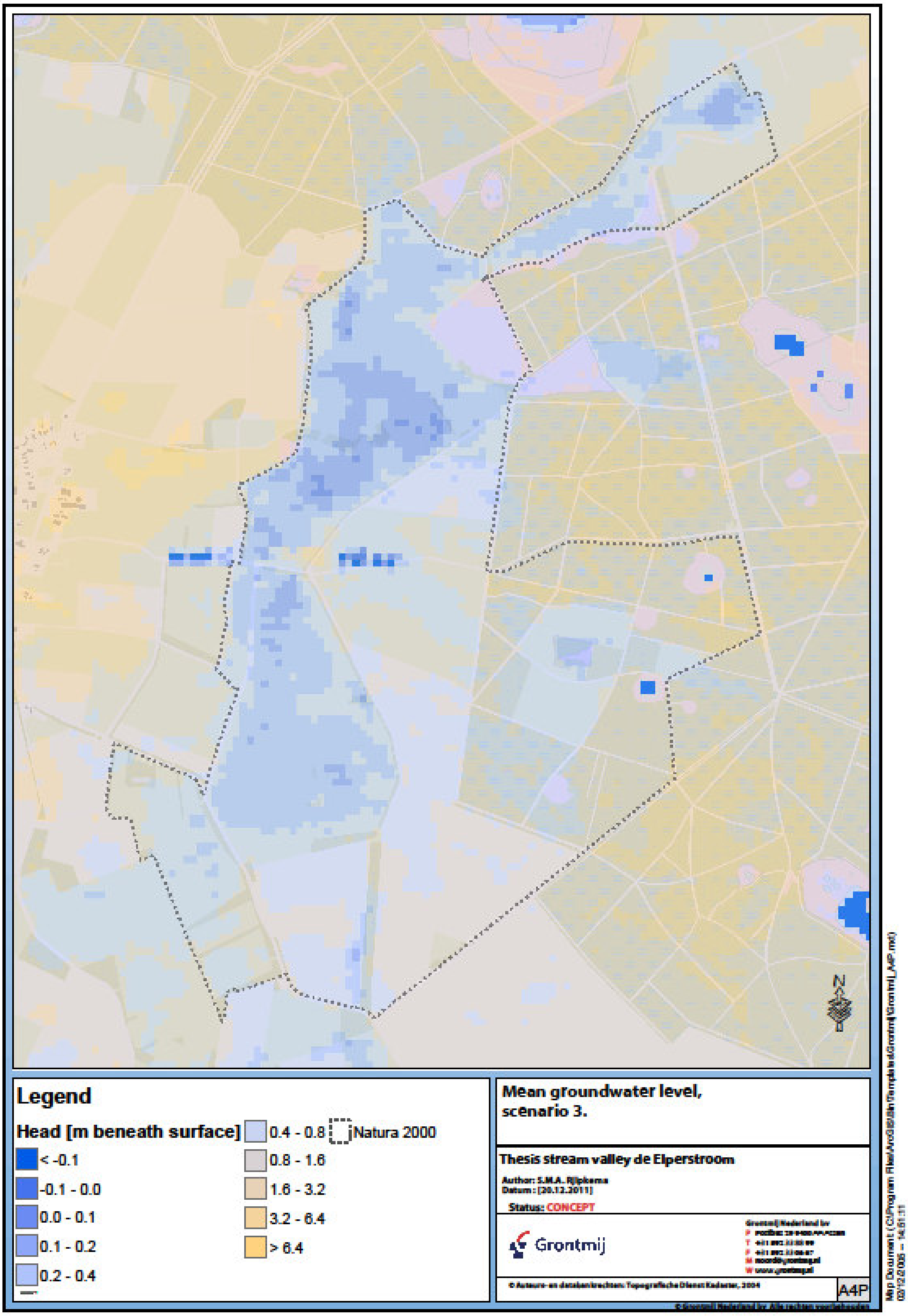
VI 46 Groundwater head layer 1, scenario 3.



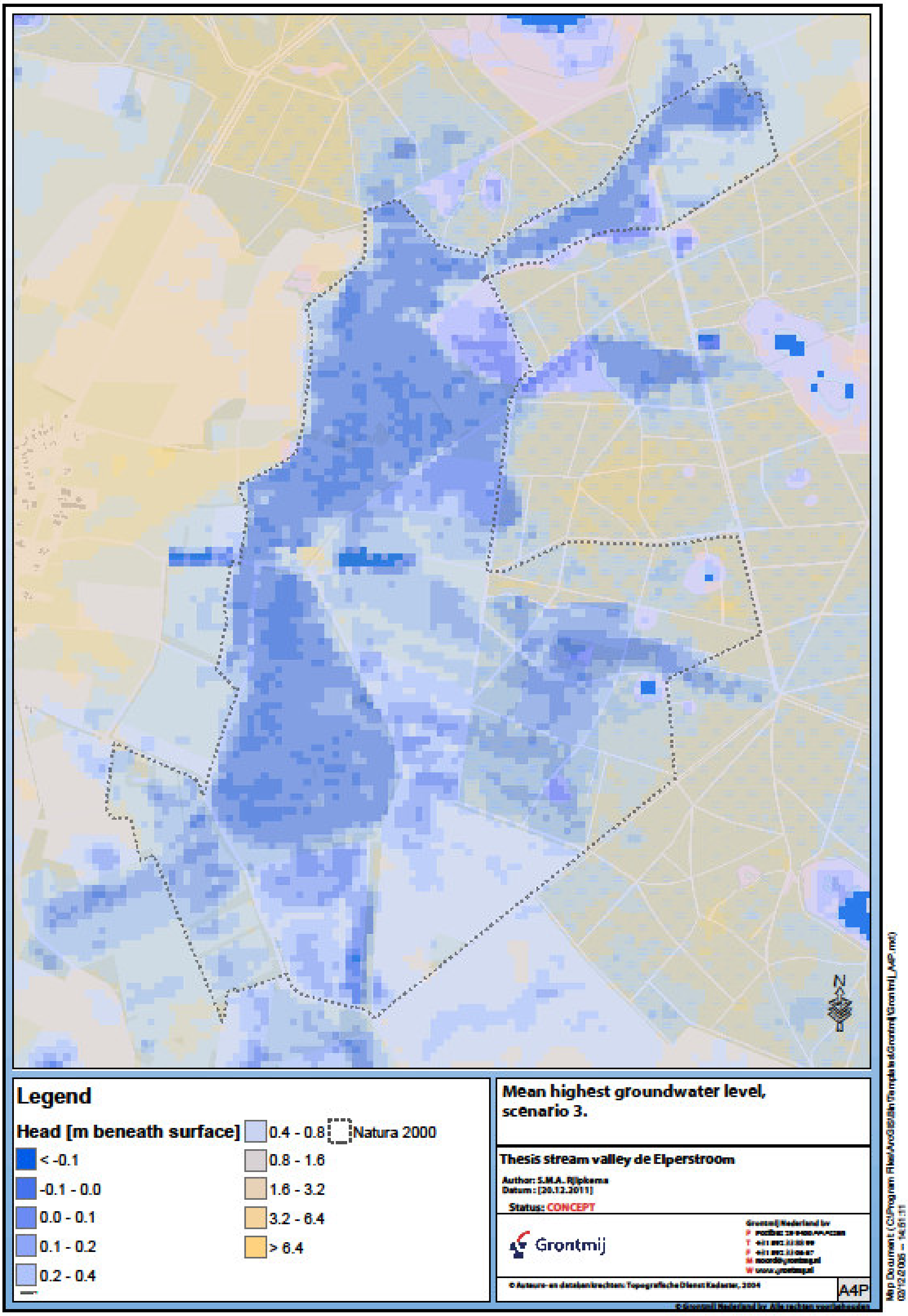
VI 47 Groundwater head layer 2, scenario 3.



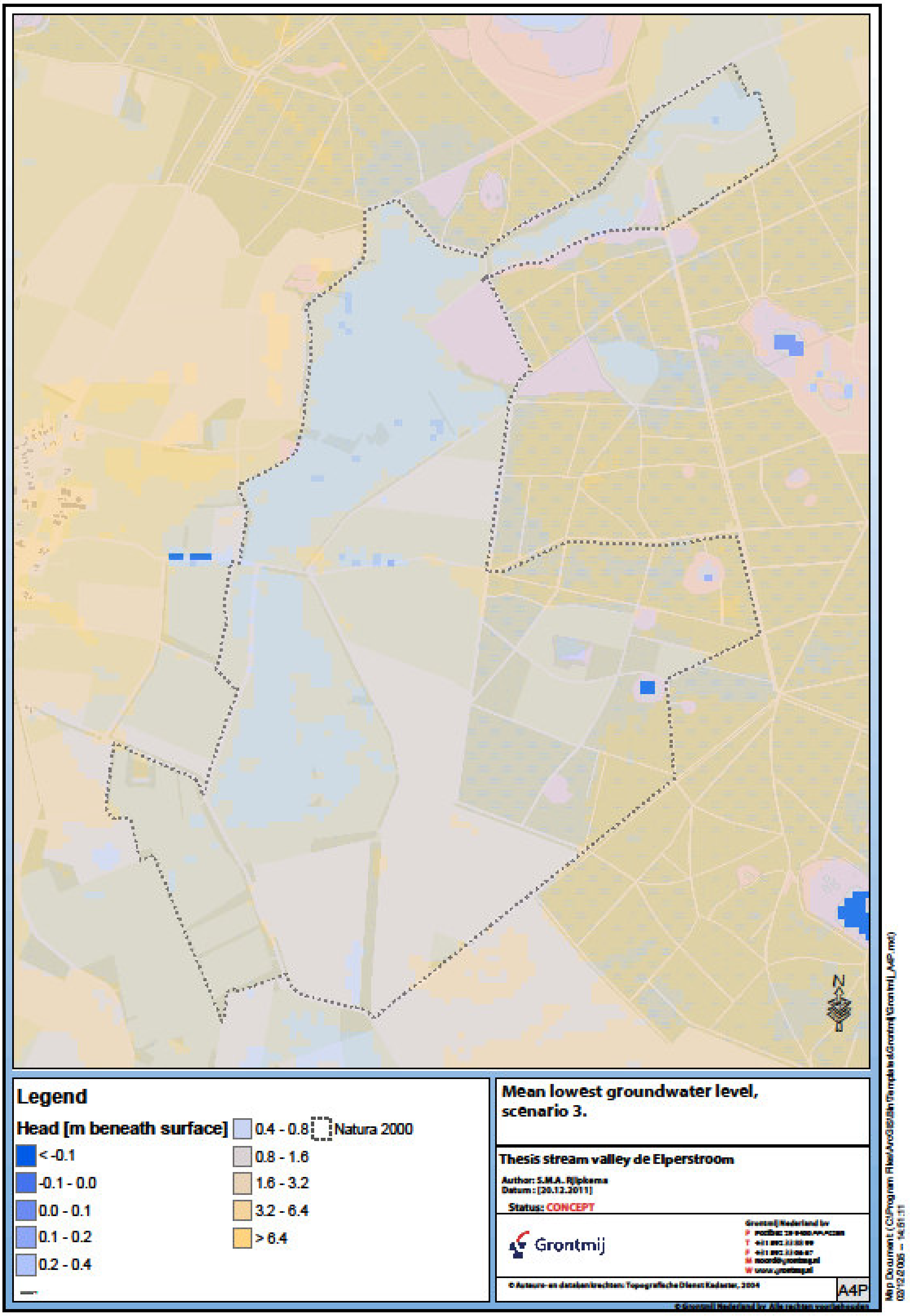
VI 48 Groundwater head layer 4, scenario 3.



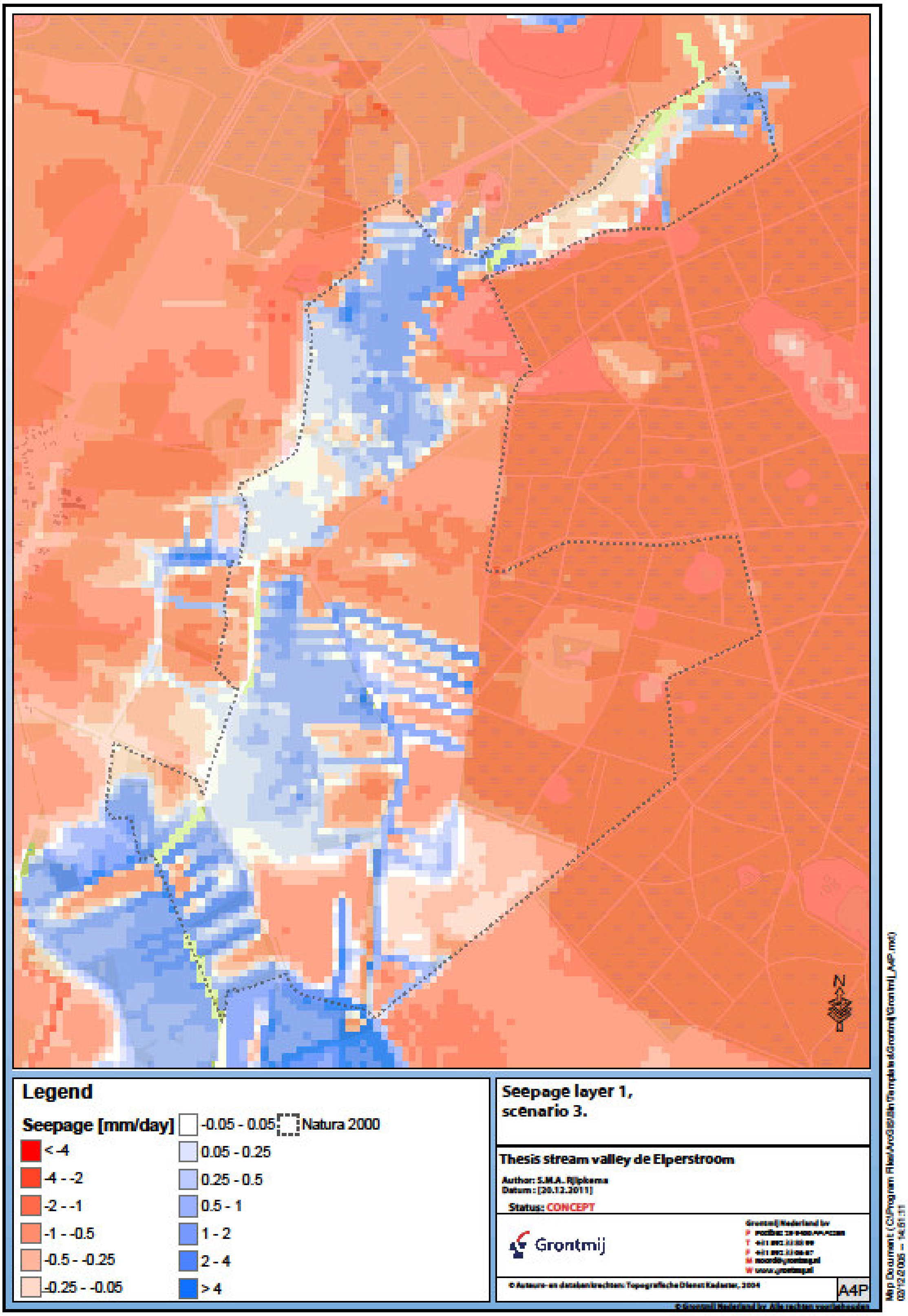
VI 49 Mean groundwater level, scenario 3.



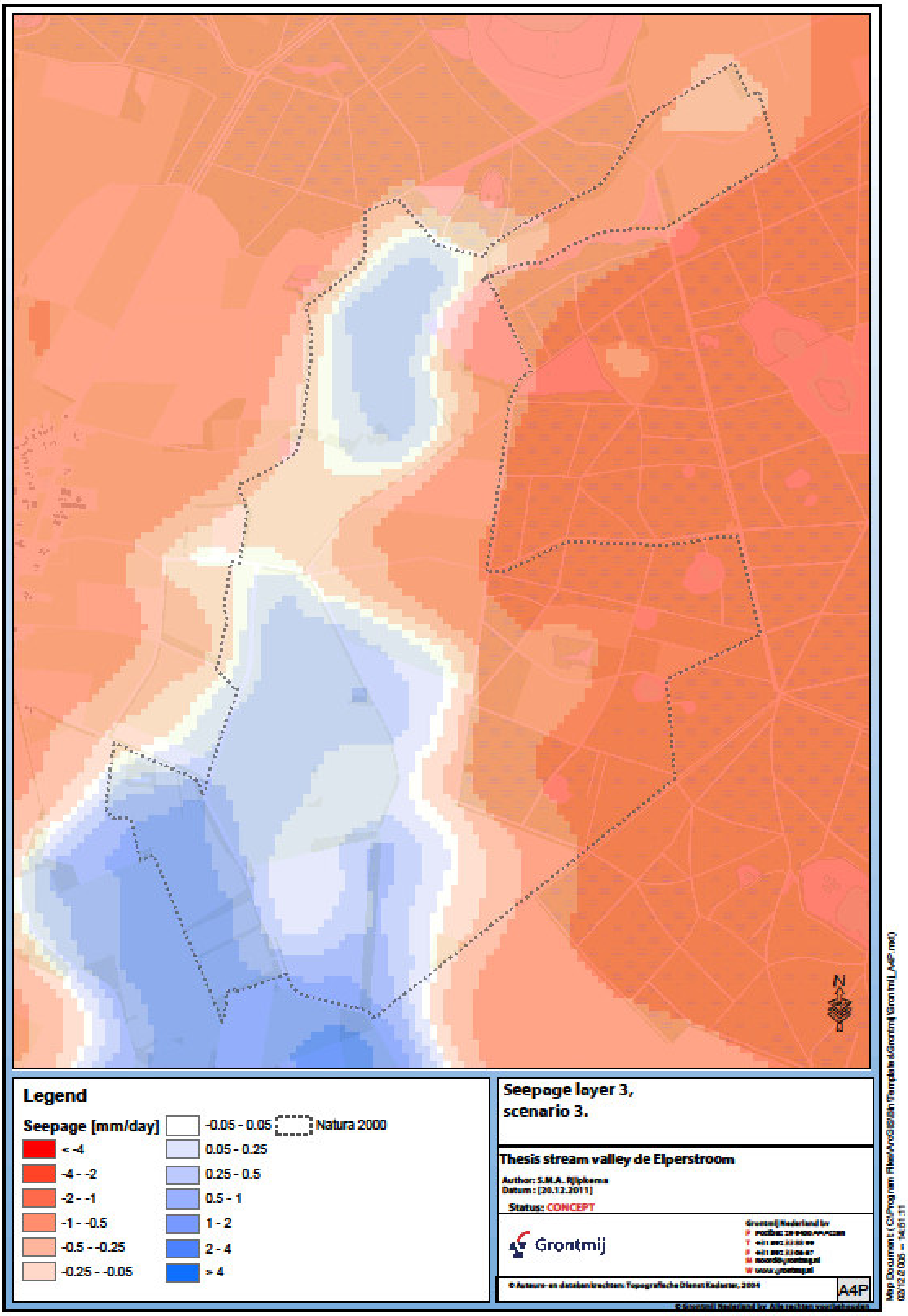
VI 50 Mean highest groundwater level, scenario 3.



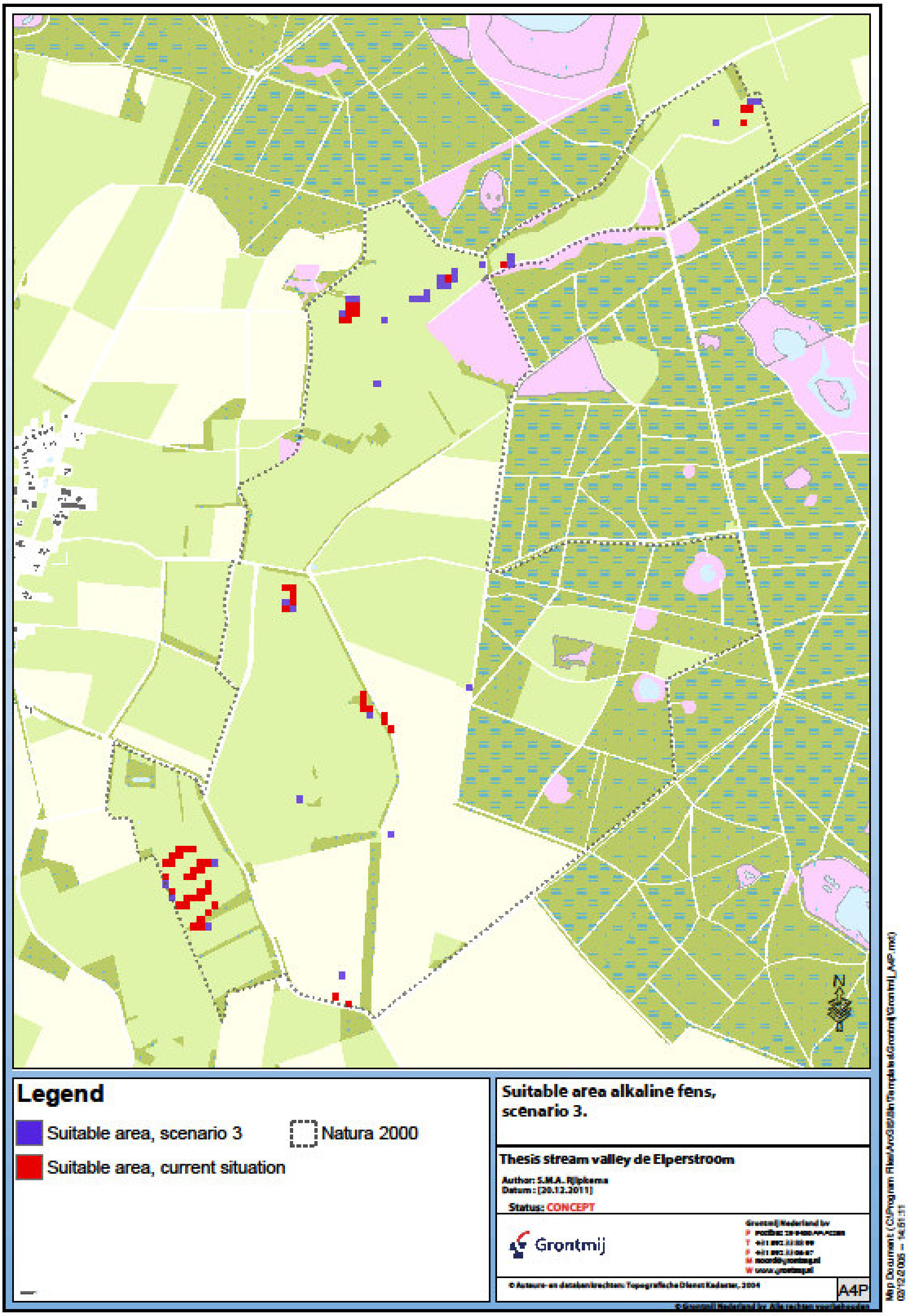
VI 51 Mean lowest groundwater level, scenario 3.



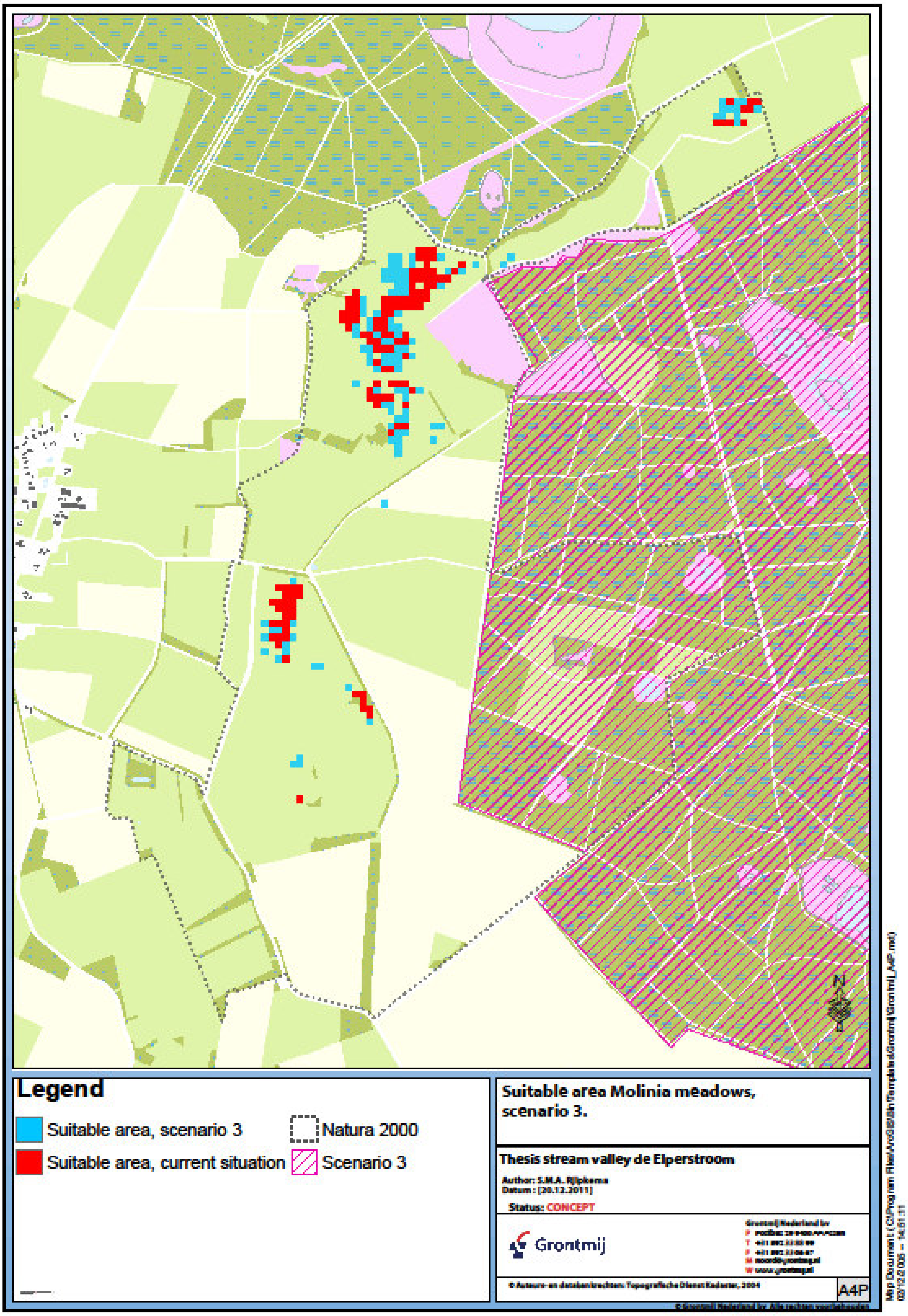
VI 52 Seepage to layer 1, scenario 3.



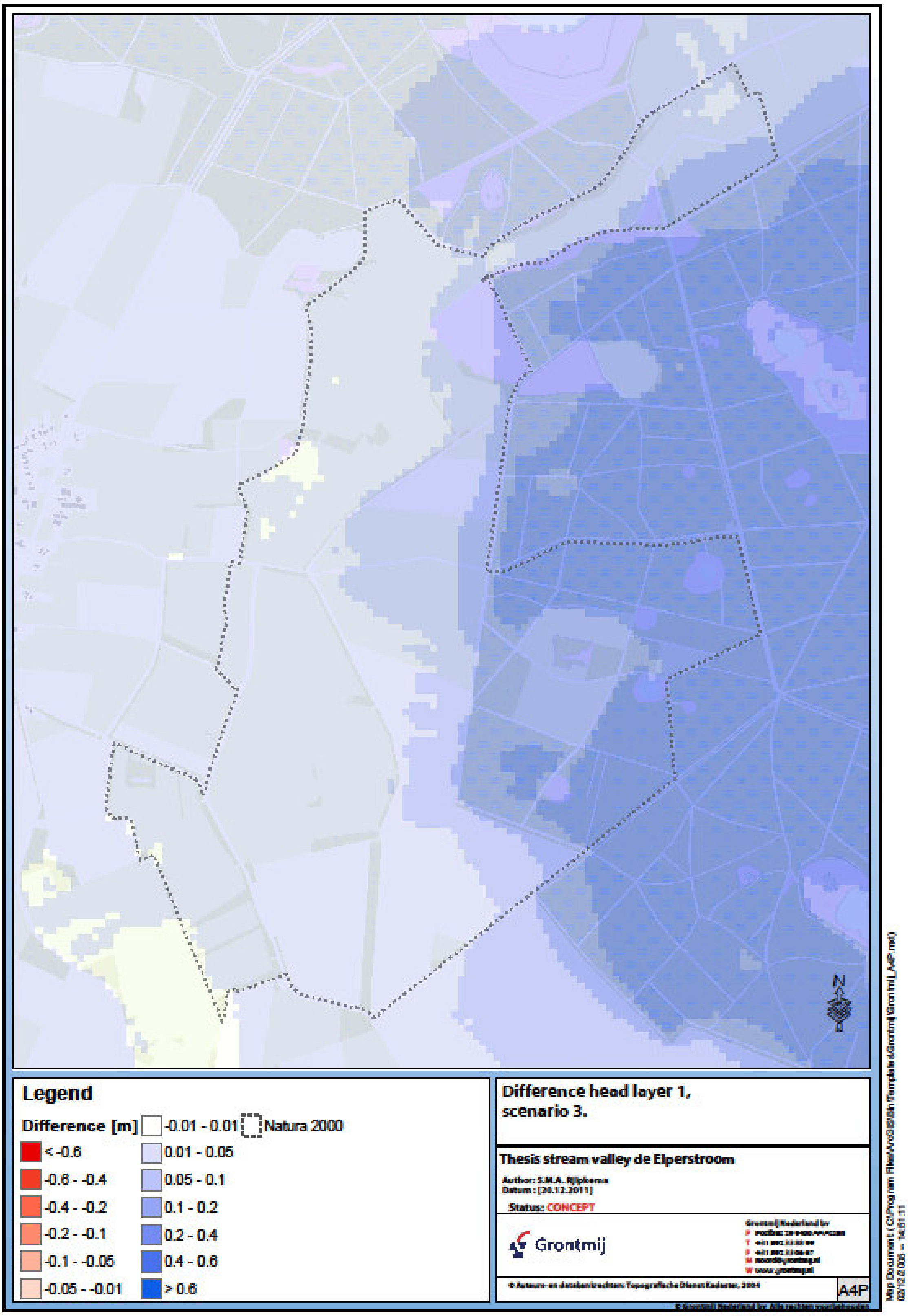
VI 53 Seepage to layer 3, scenario 3.



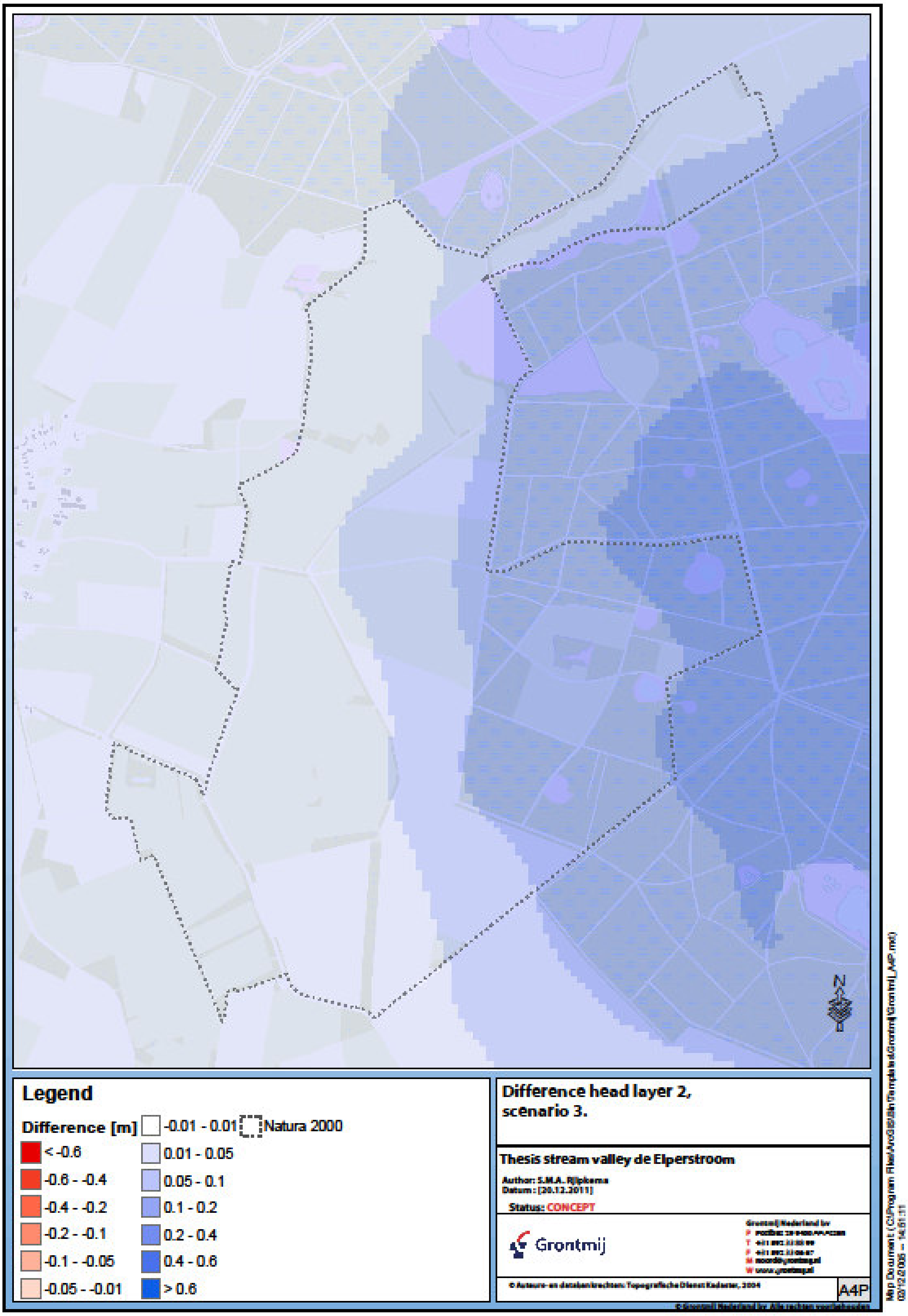
VI 54 Suitable area alkaline fens, scenario 3.



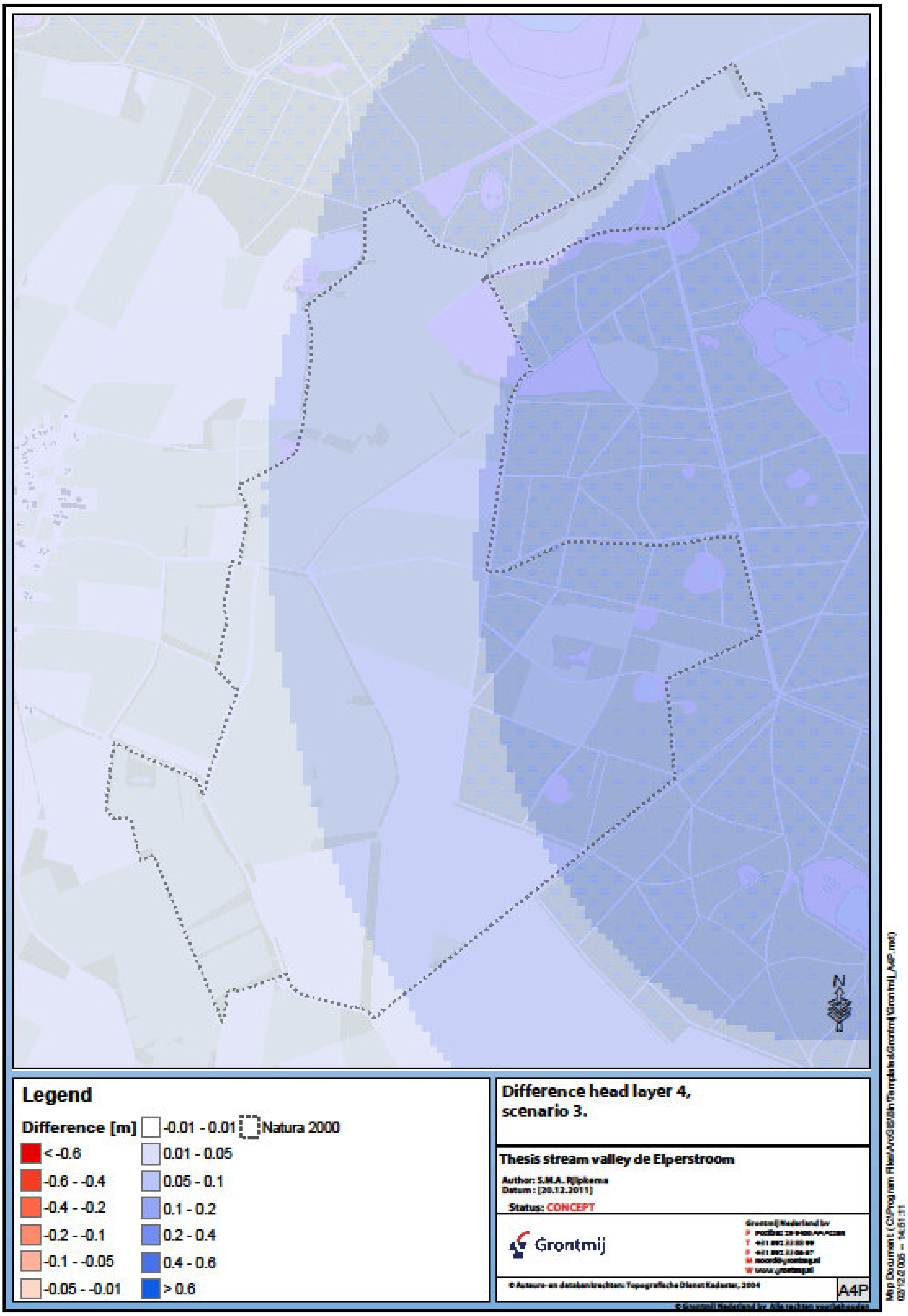
VI 55 Suitable area Molinia meadows, scenario 3.



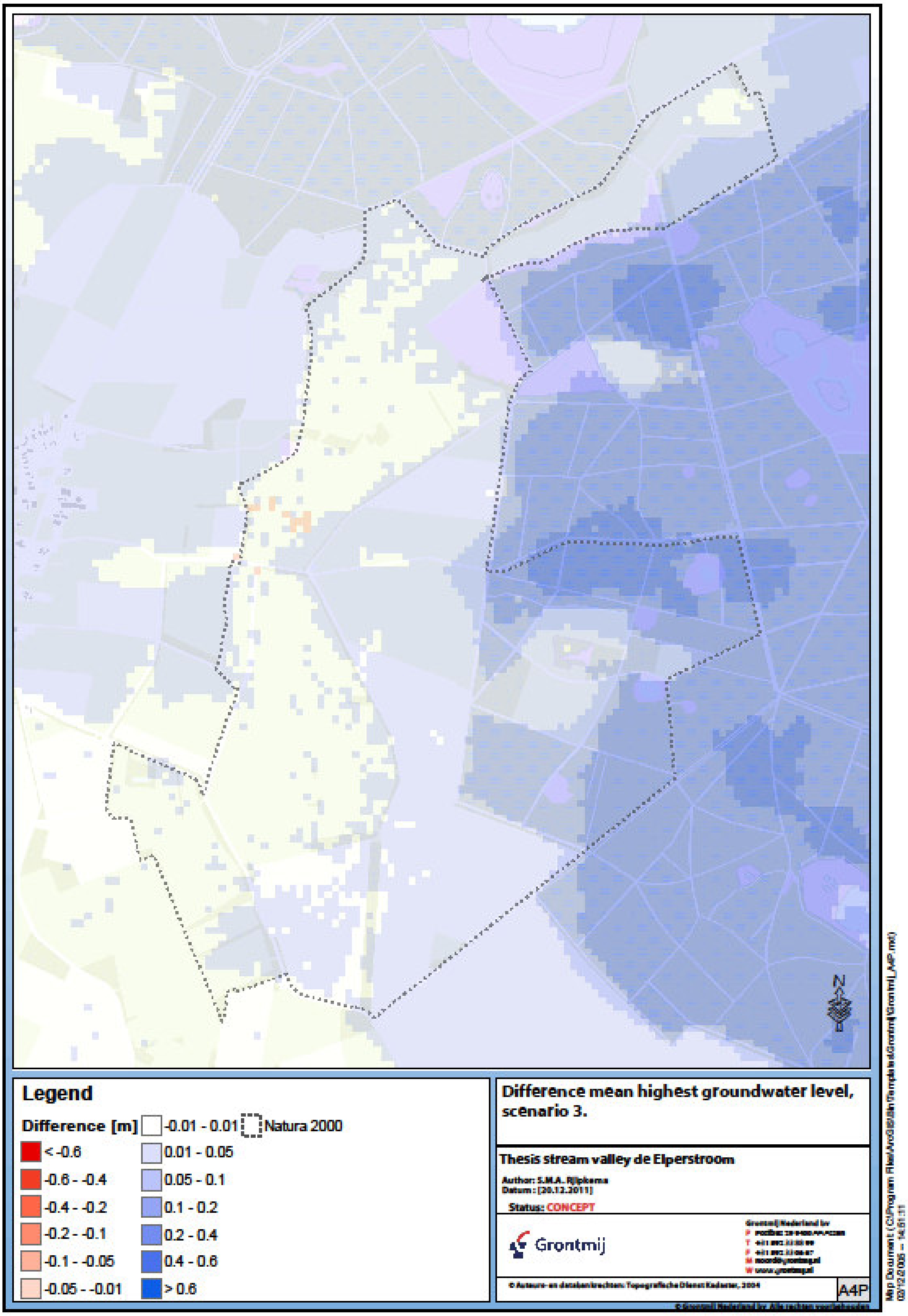
VI 56 Difference head layer 1, scenario 3.



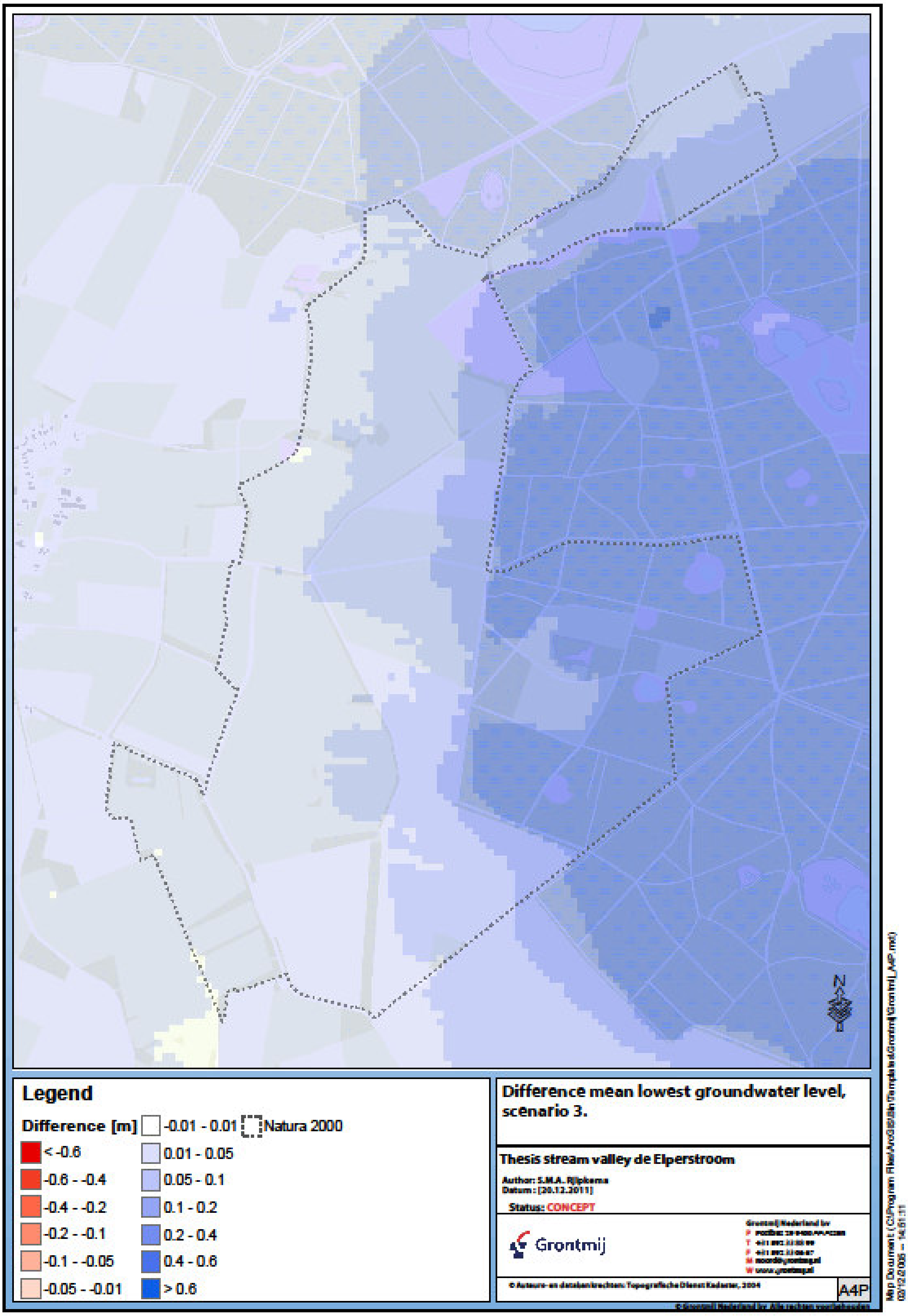
VI 57 Difference head layer 2, scenario 3.



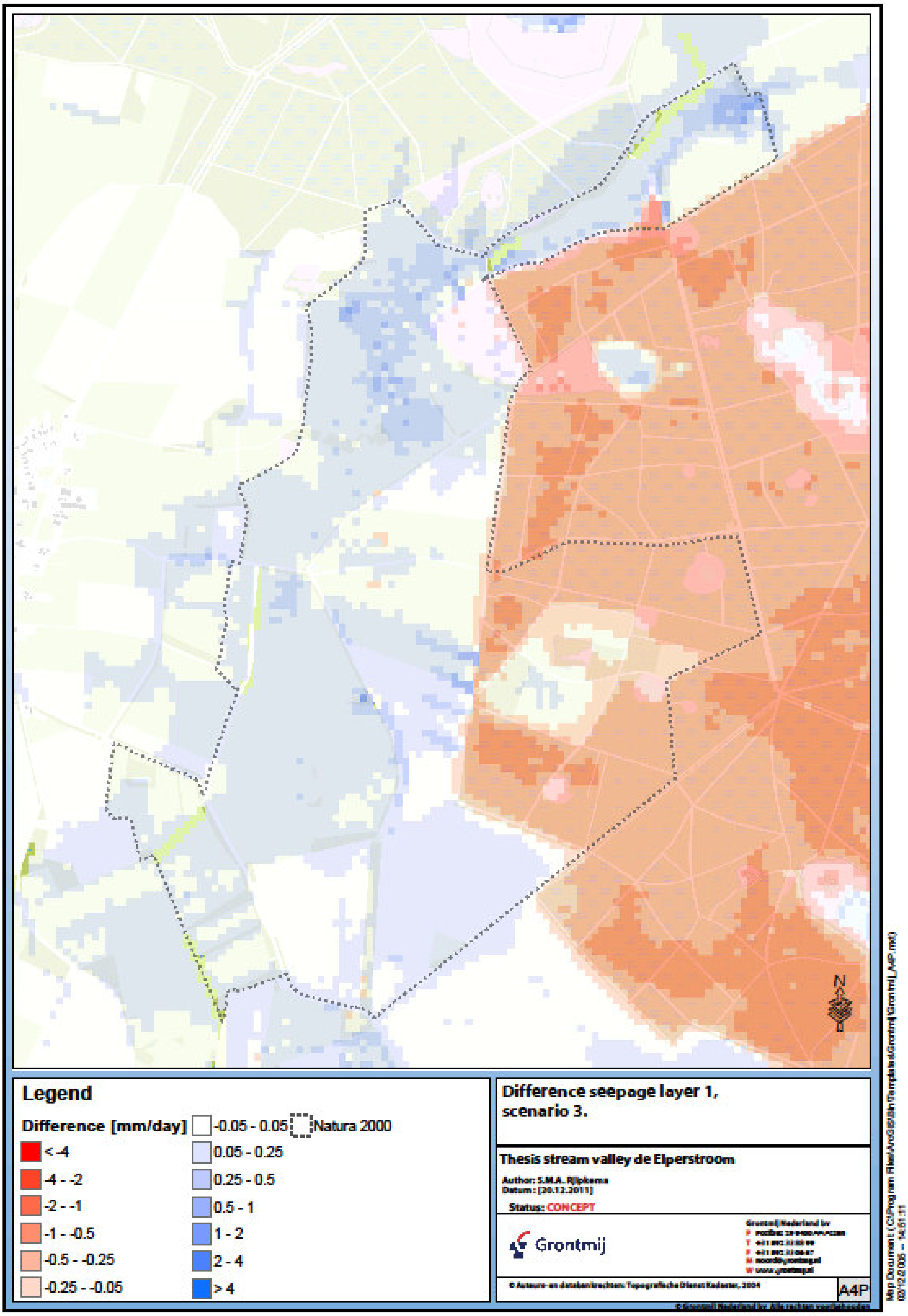
VI 58 Difference head layer 4, scenario 3.



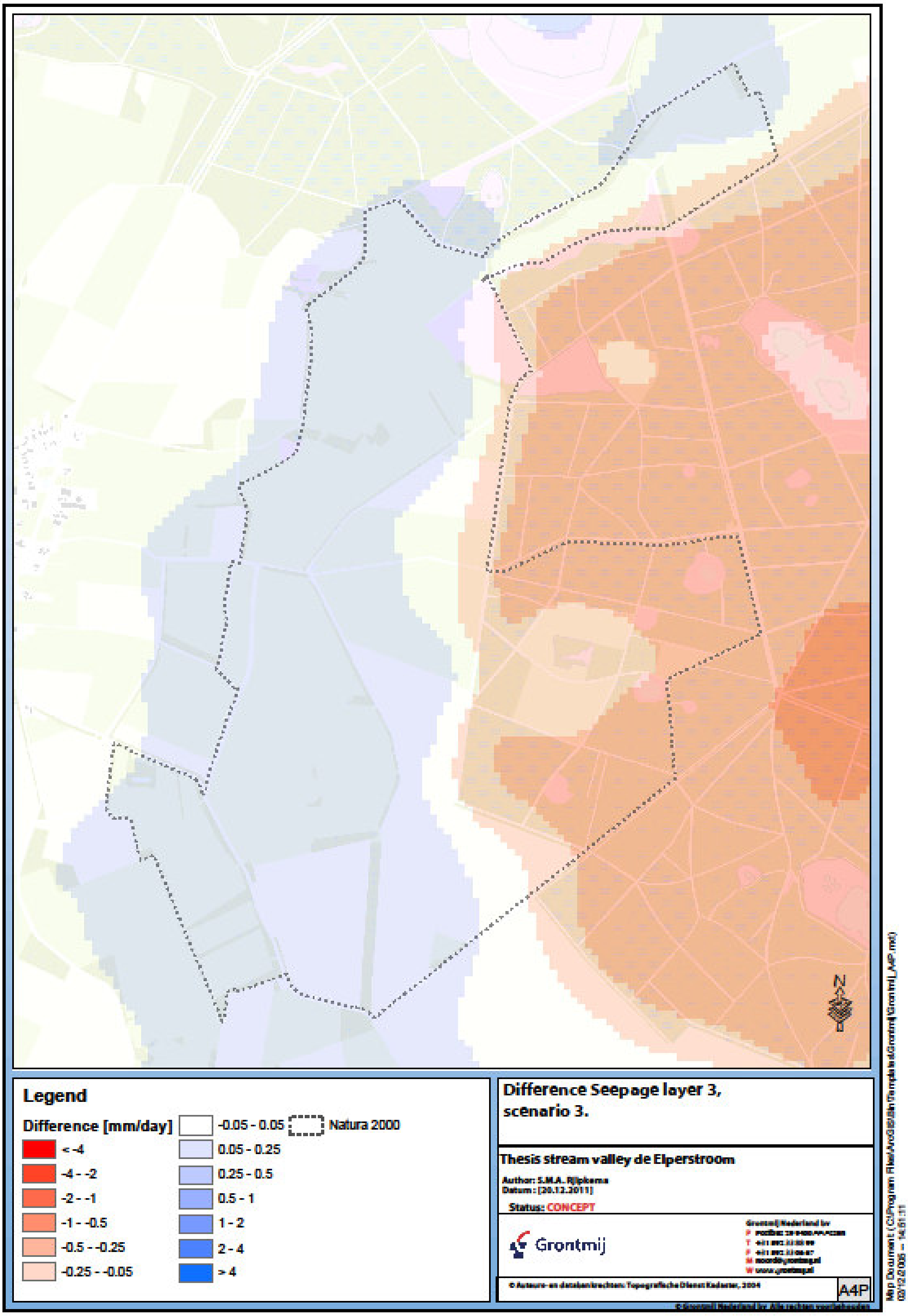
VI 59 Difference mean highest groundwater level, scenario 3.



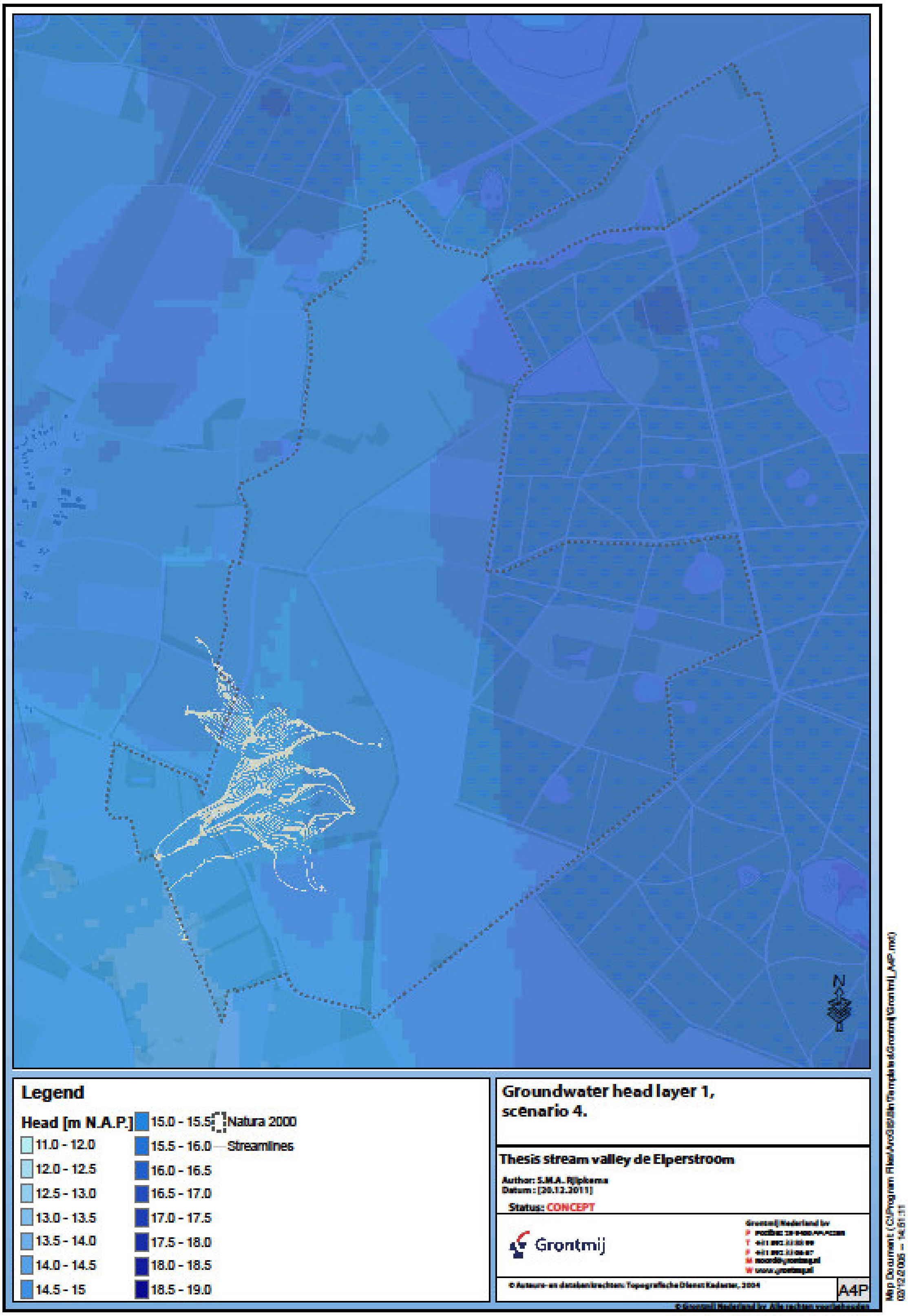
VI 60 Difference mean lowest groundwater level, scenario 3.



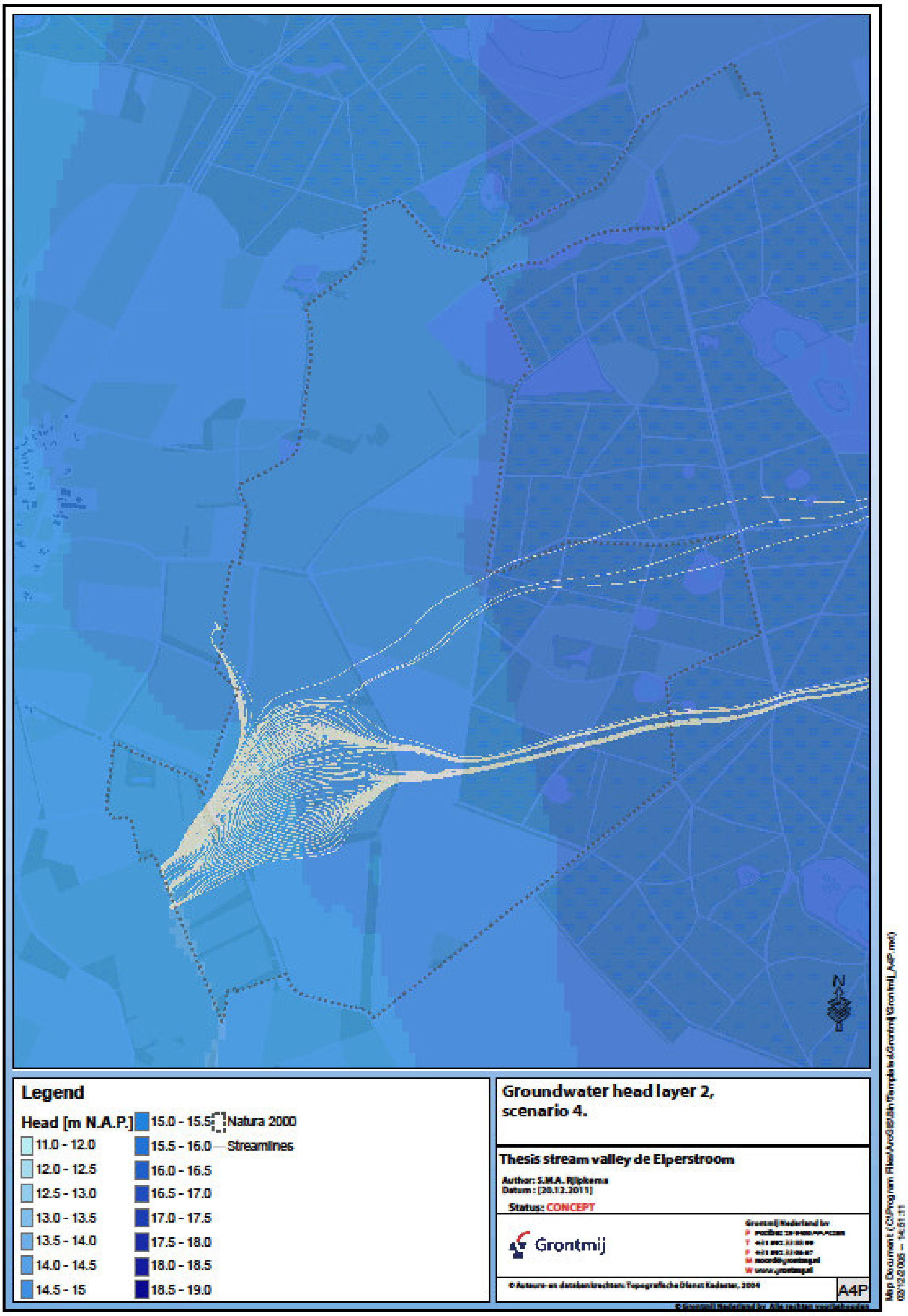
VI 61 Difference in the seepage to layer 1, scenario 3.



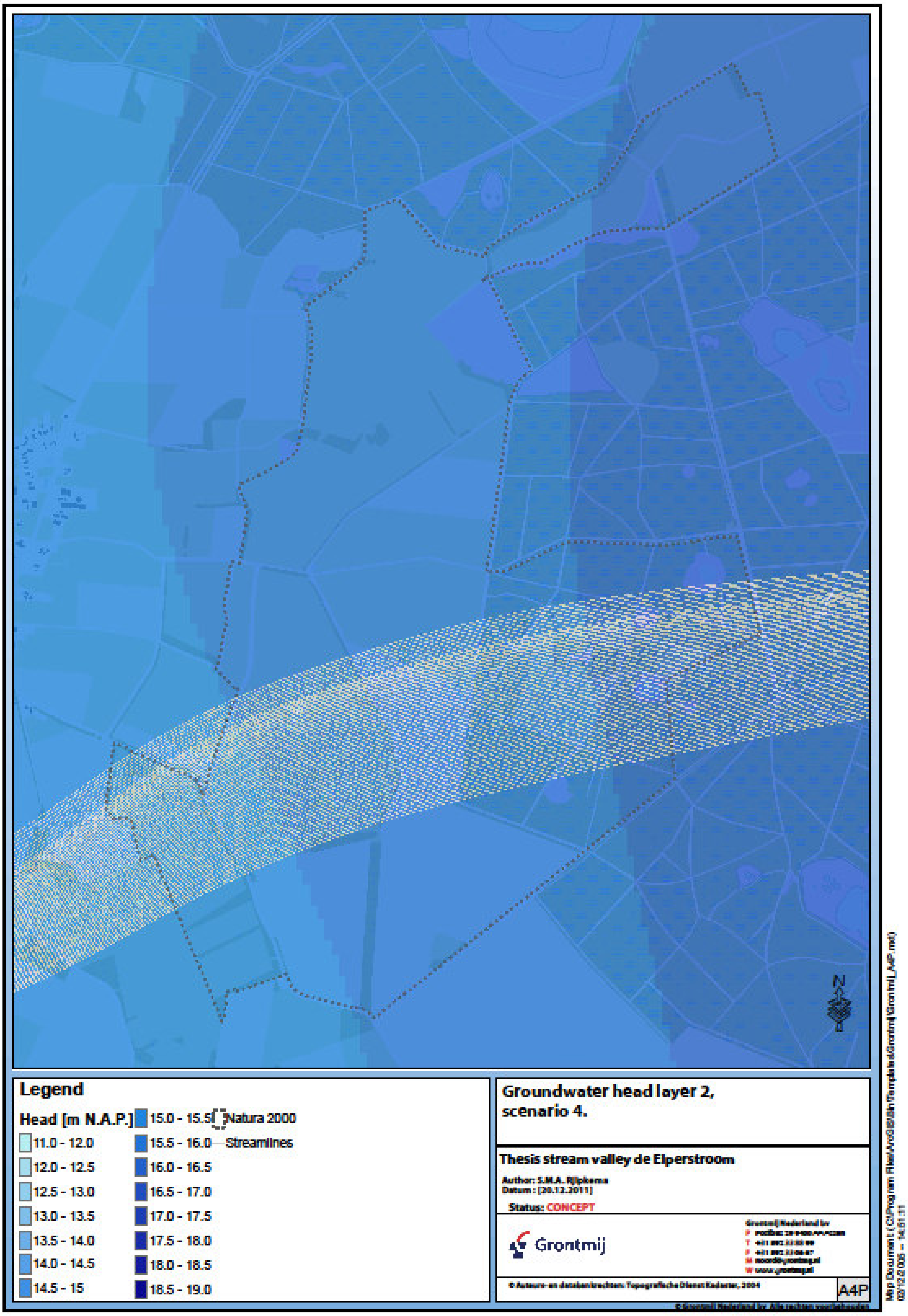
VI 62 Difference seepage to layer 3, scenario 3.



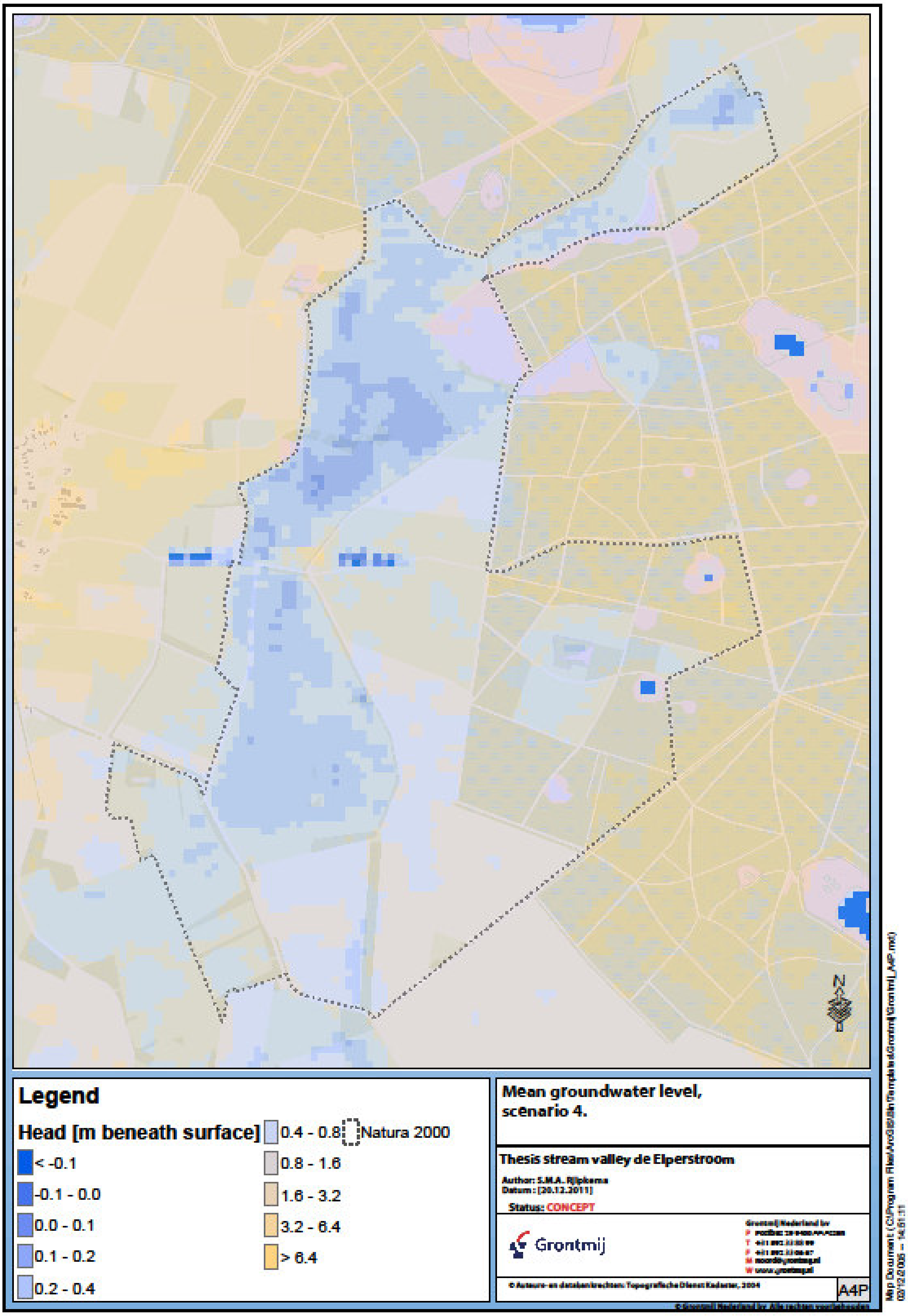
VI 63 Head layer 1, scenario 4.



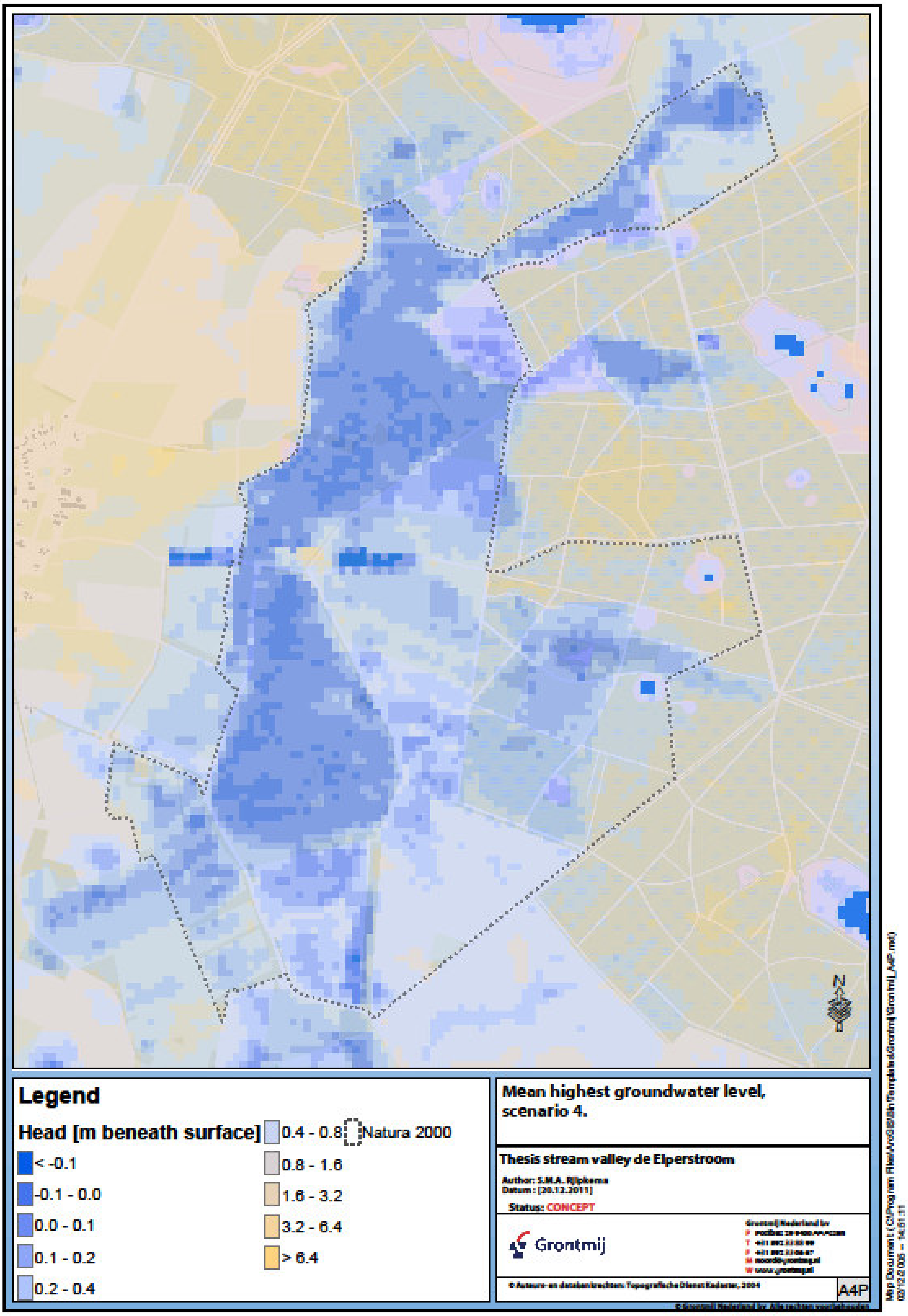
VI 64 Head layer 2, scenario 4.



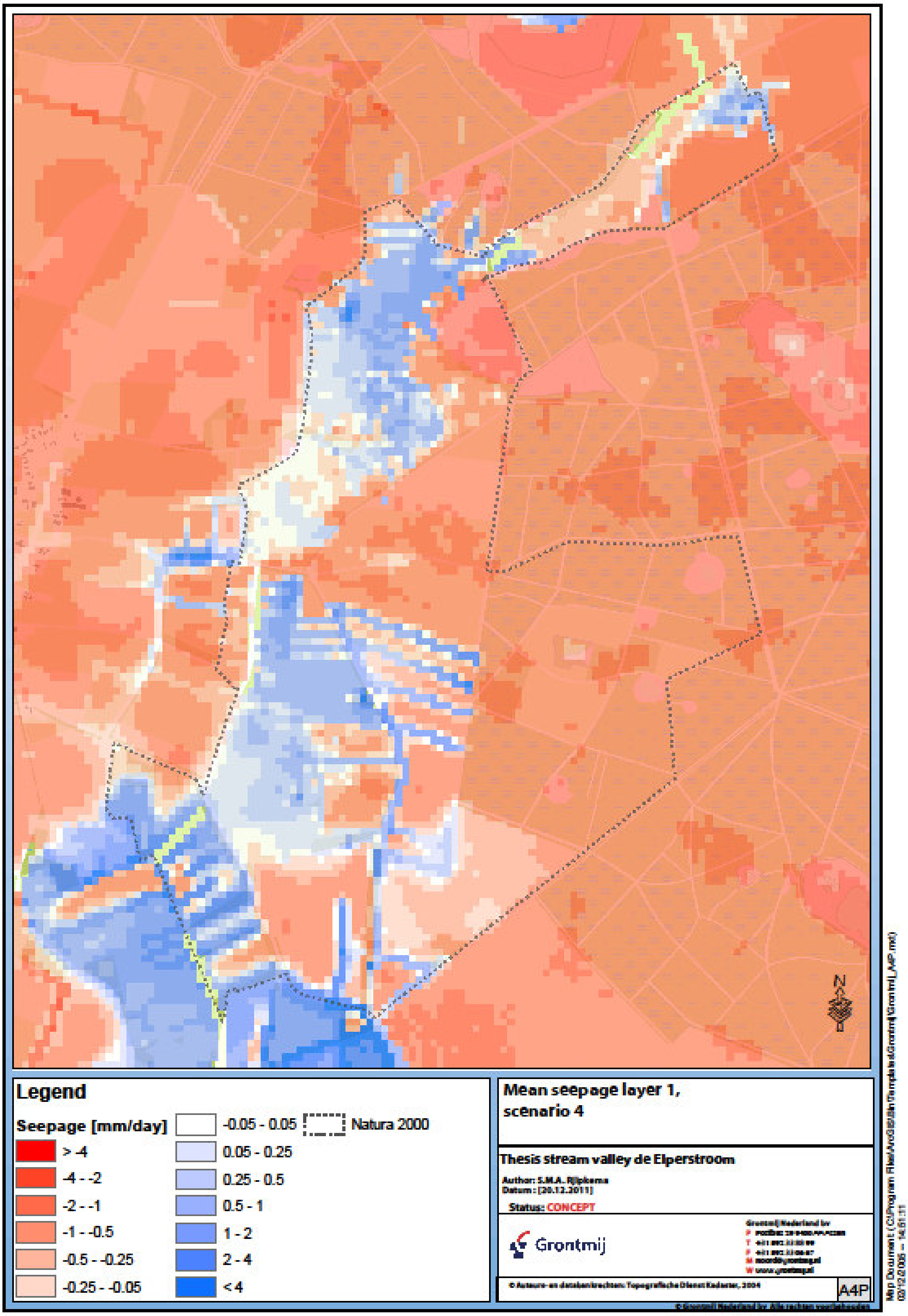
VI 65 Head layer 4, scenario 4.



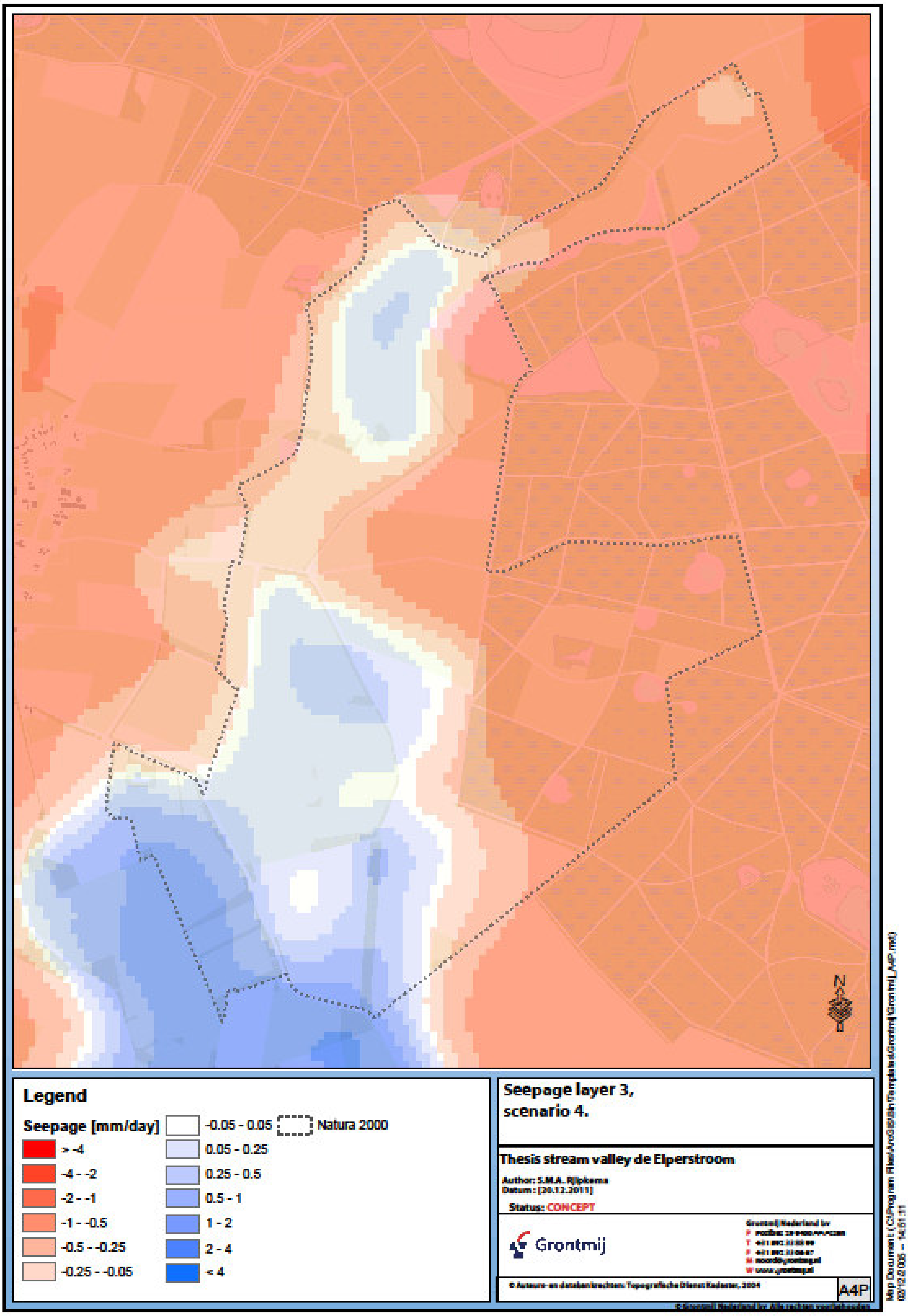
VI 66 Mean groundwater level, scenario 4.



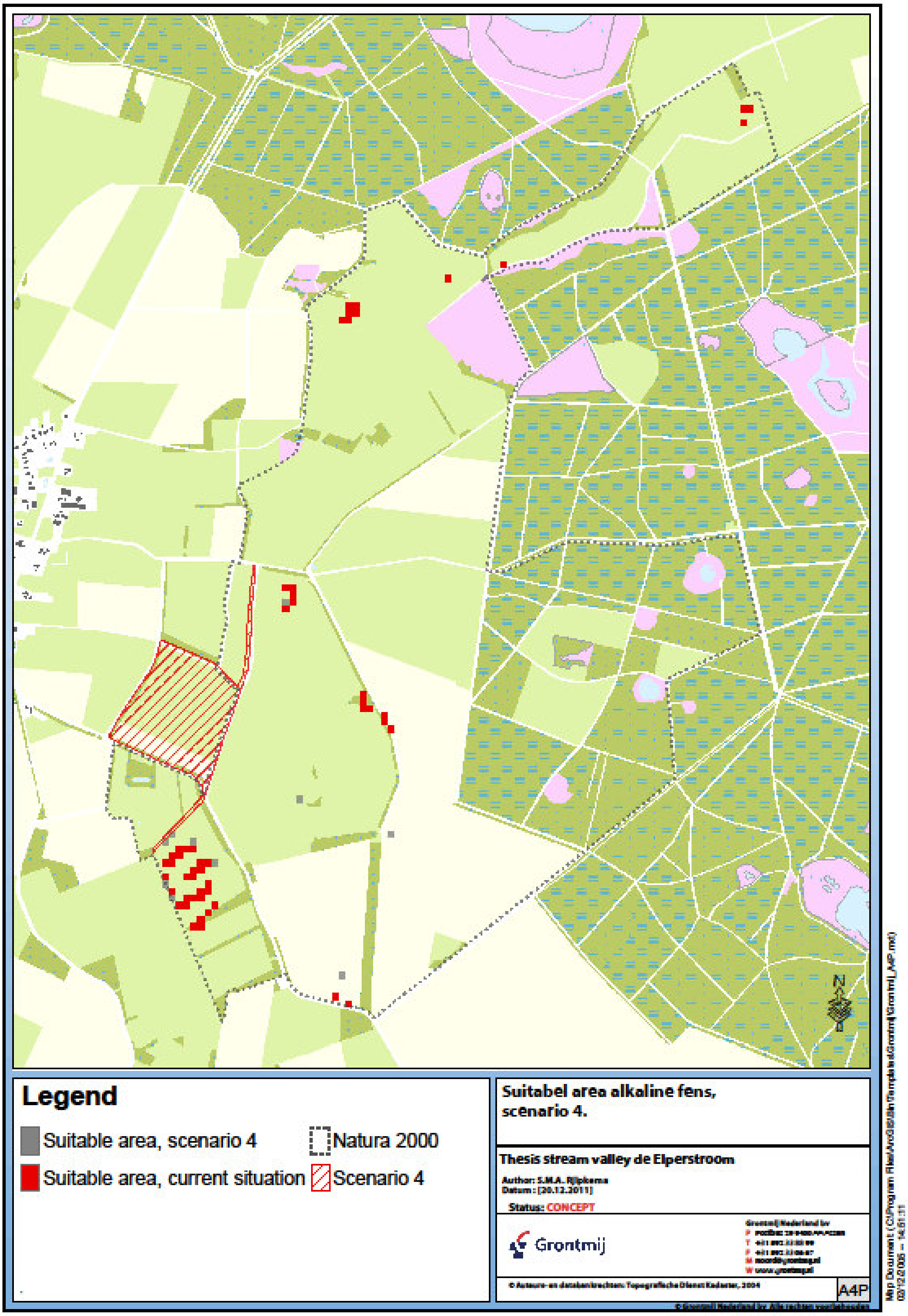
VI 67 Mean highest groundwater level, scenario 4.



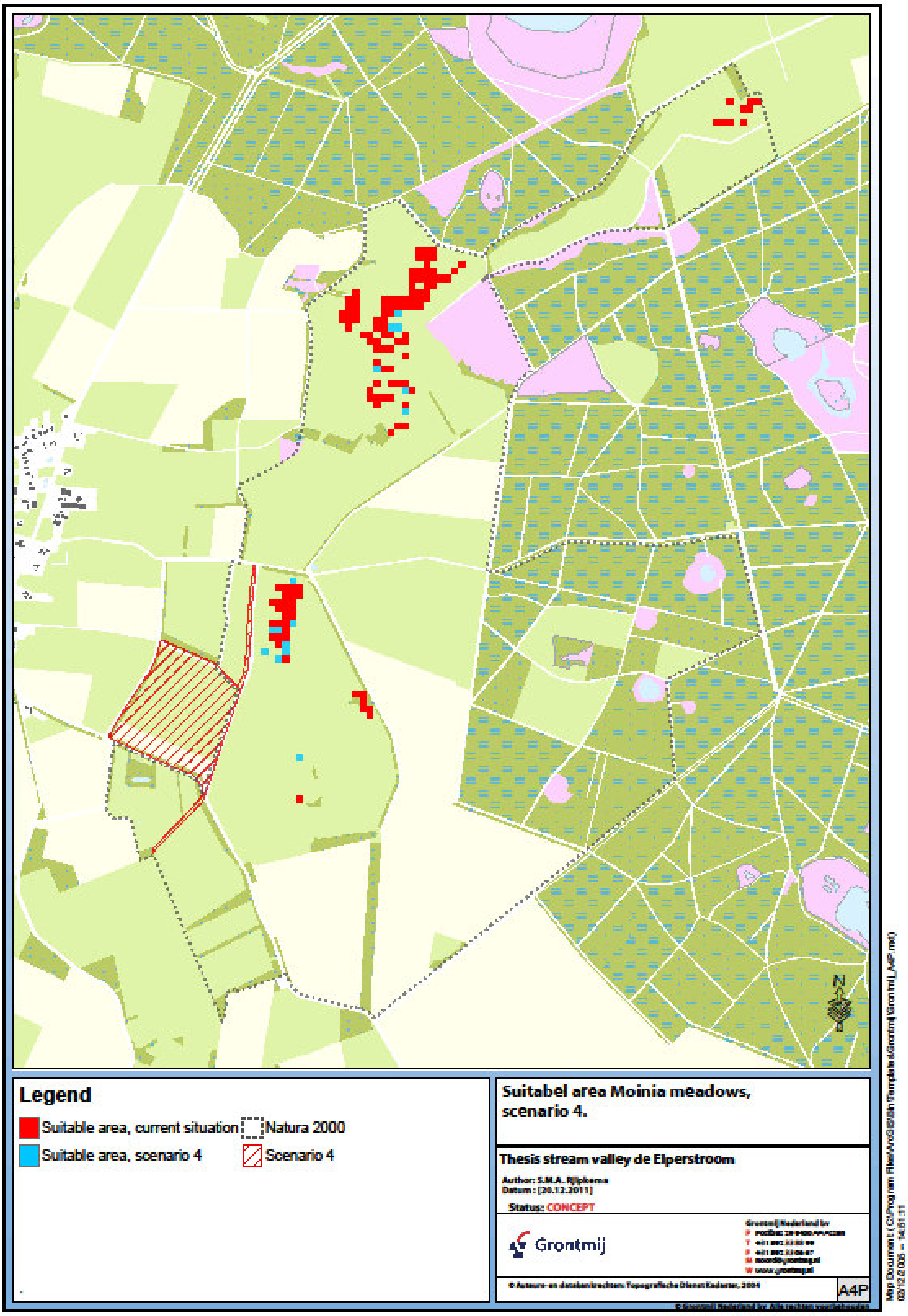
VI 68 Seepage to layer 1, scenario 4.



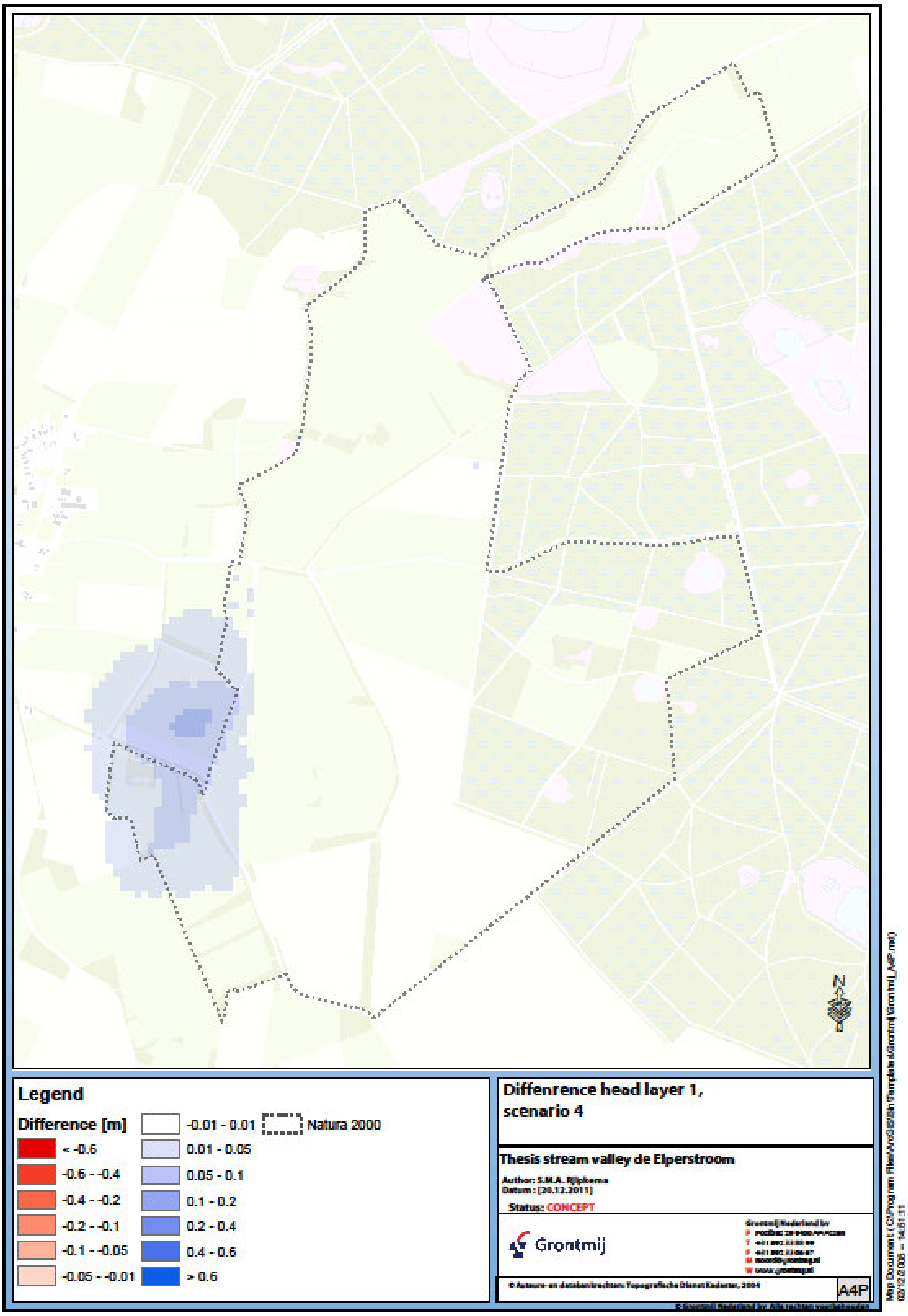
VI 69 Seepage to layer 3, scenario 4.



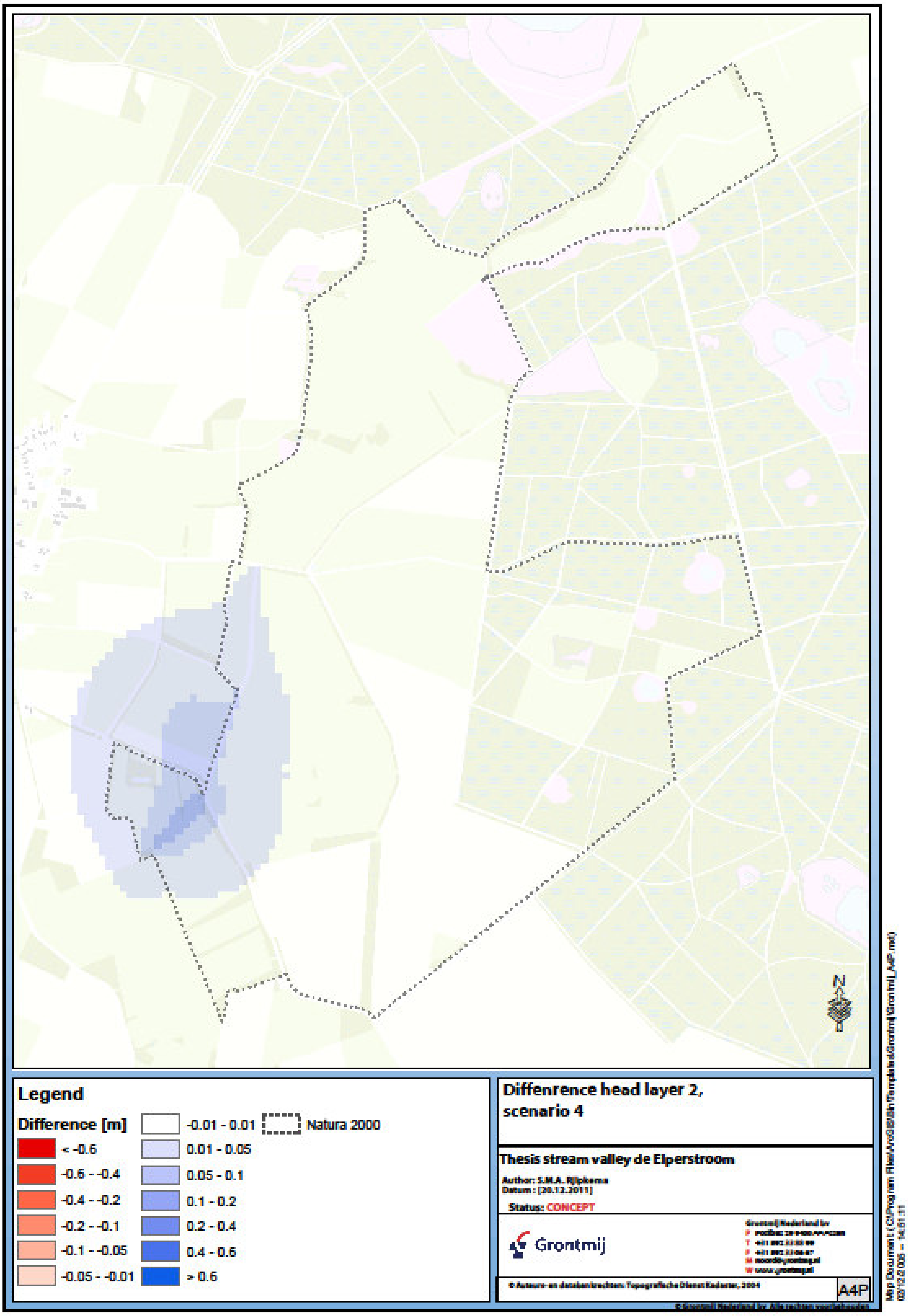
VI 70 Area suitable for alkaline fens, scenario 4.



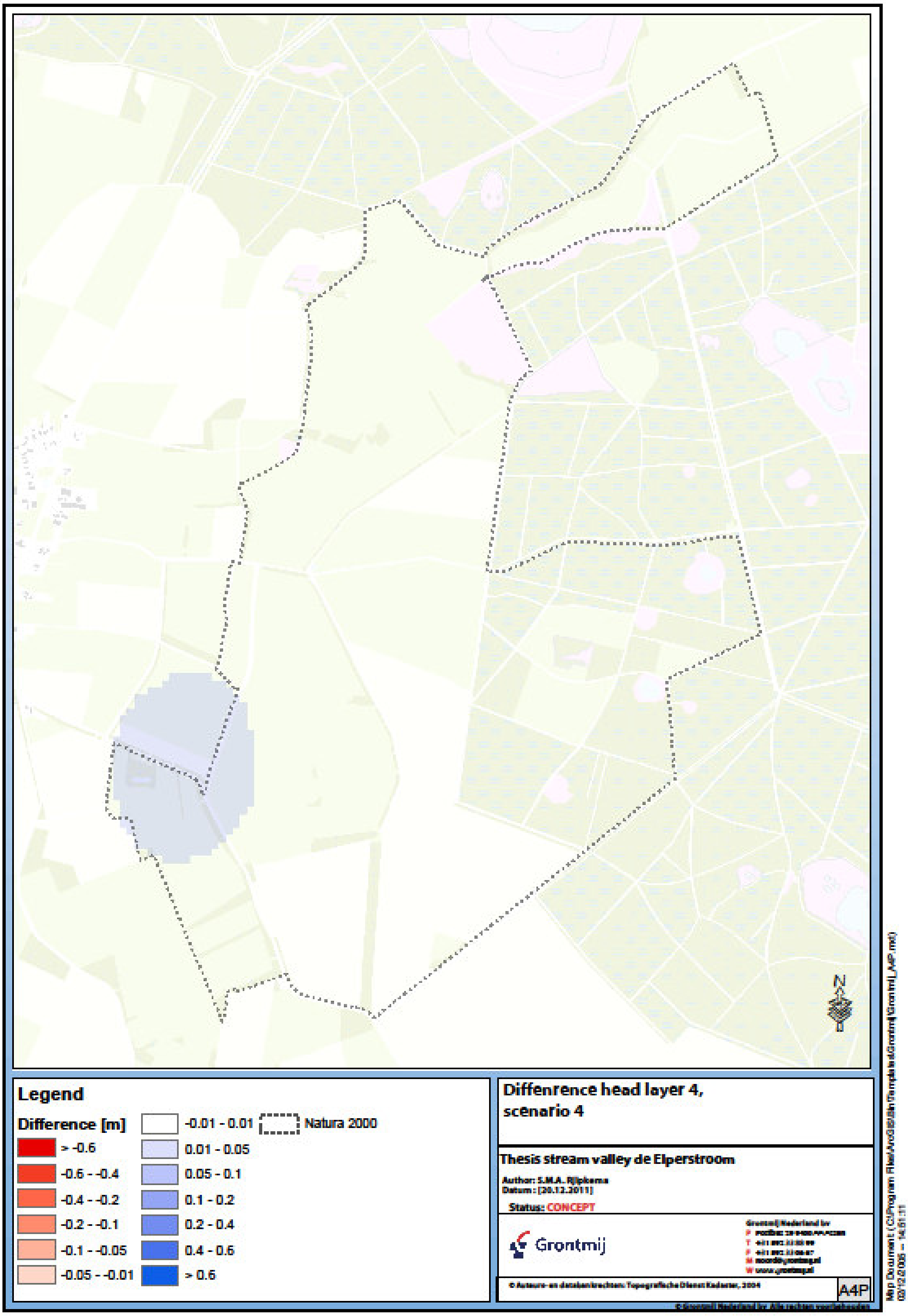
VI 71 Area suitable for Molinia meadows, scenario 4.



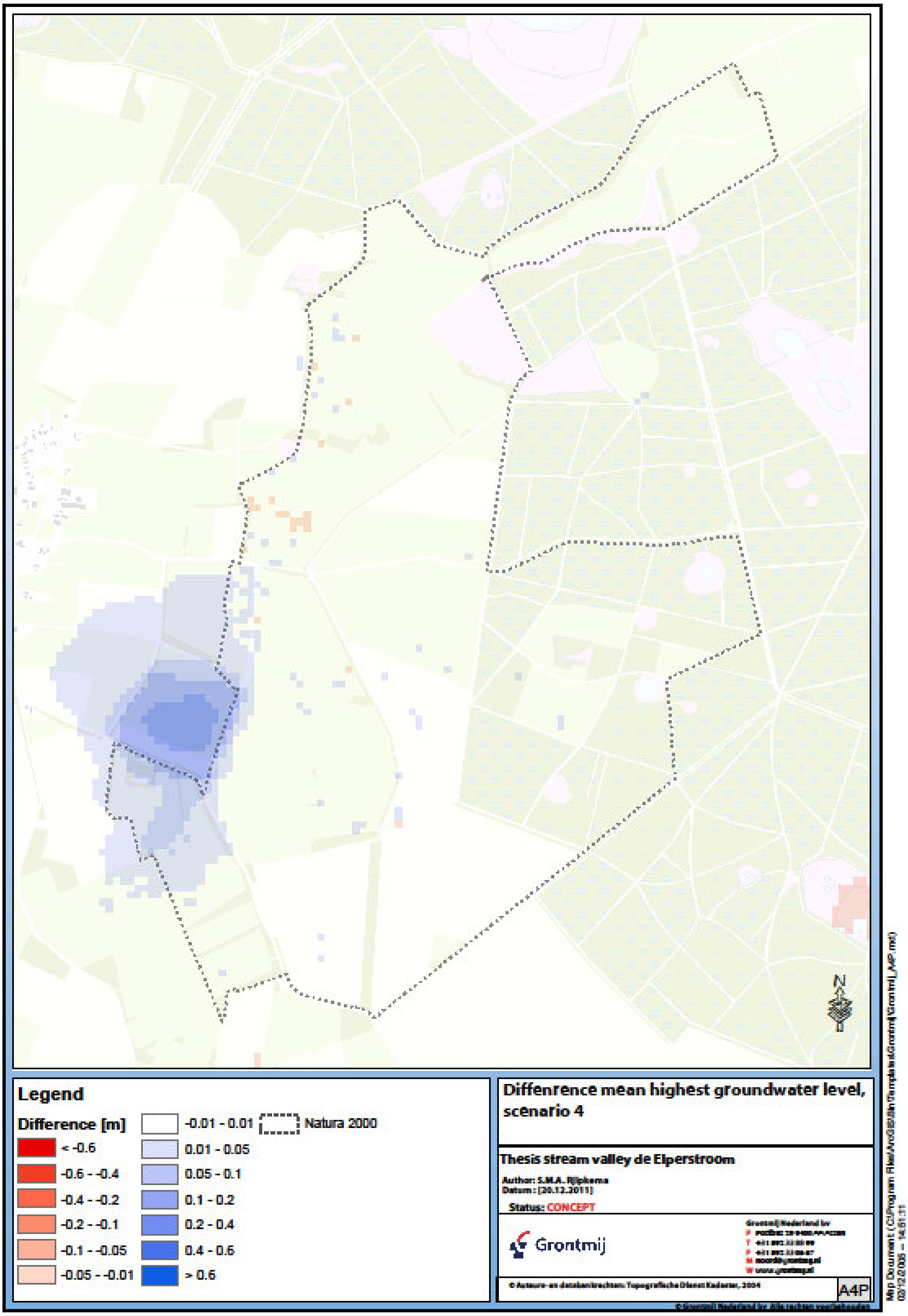
VI 72 Difference head layer 1, scenario 4.



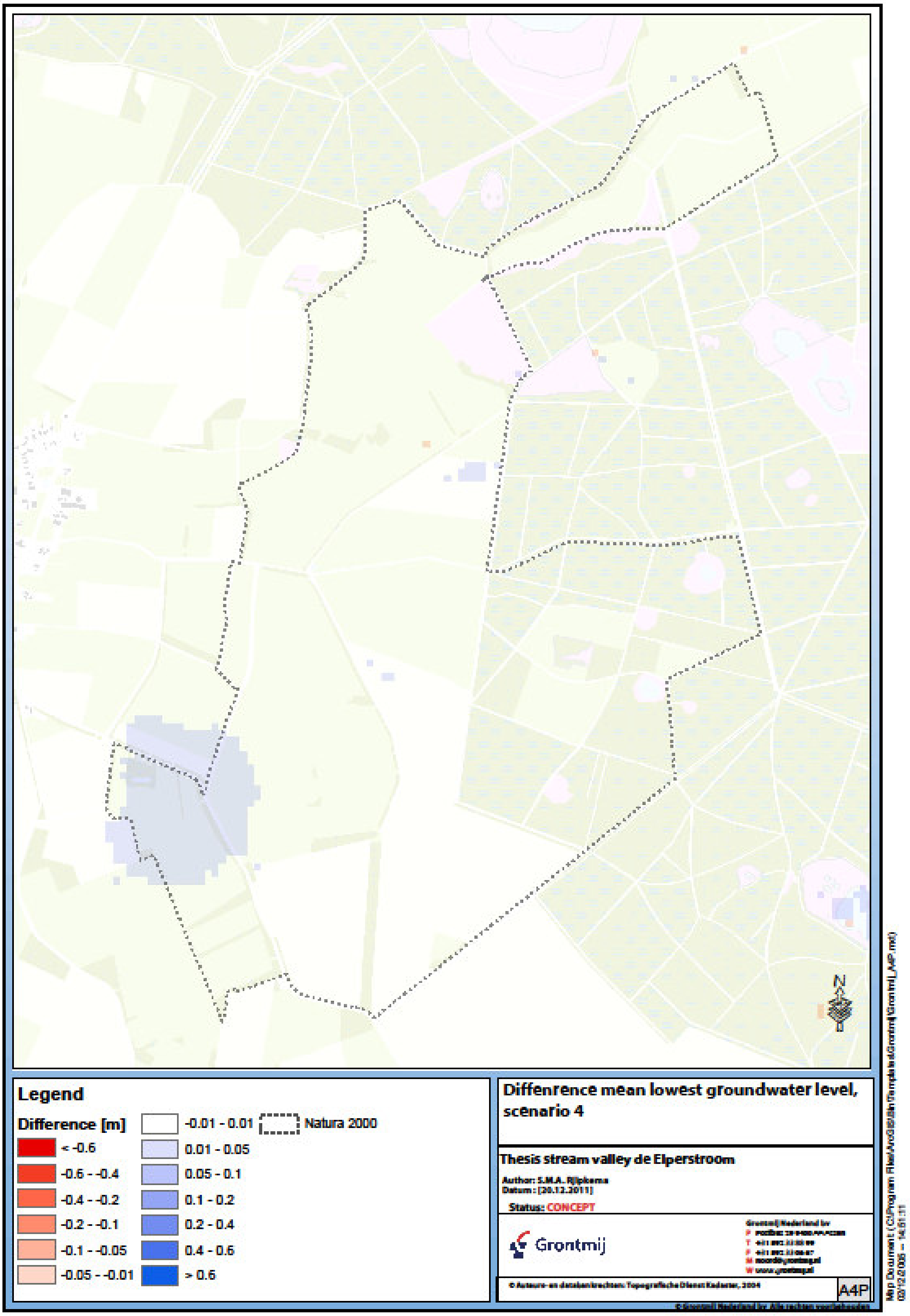
VI 73 Difference head layer 2, scenario 4.



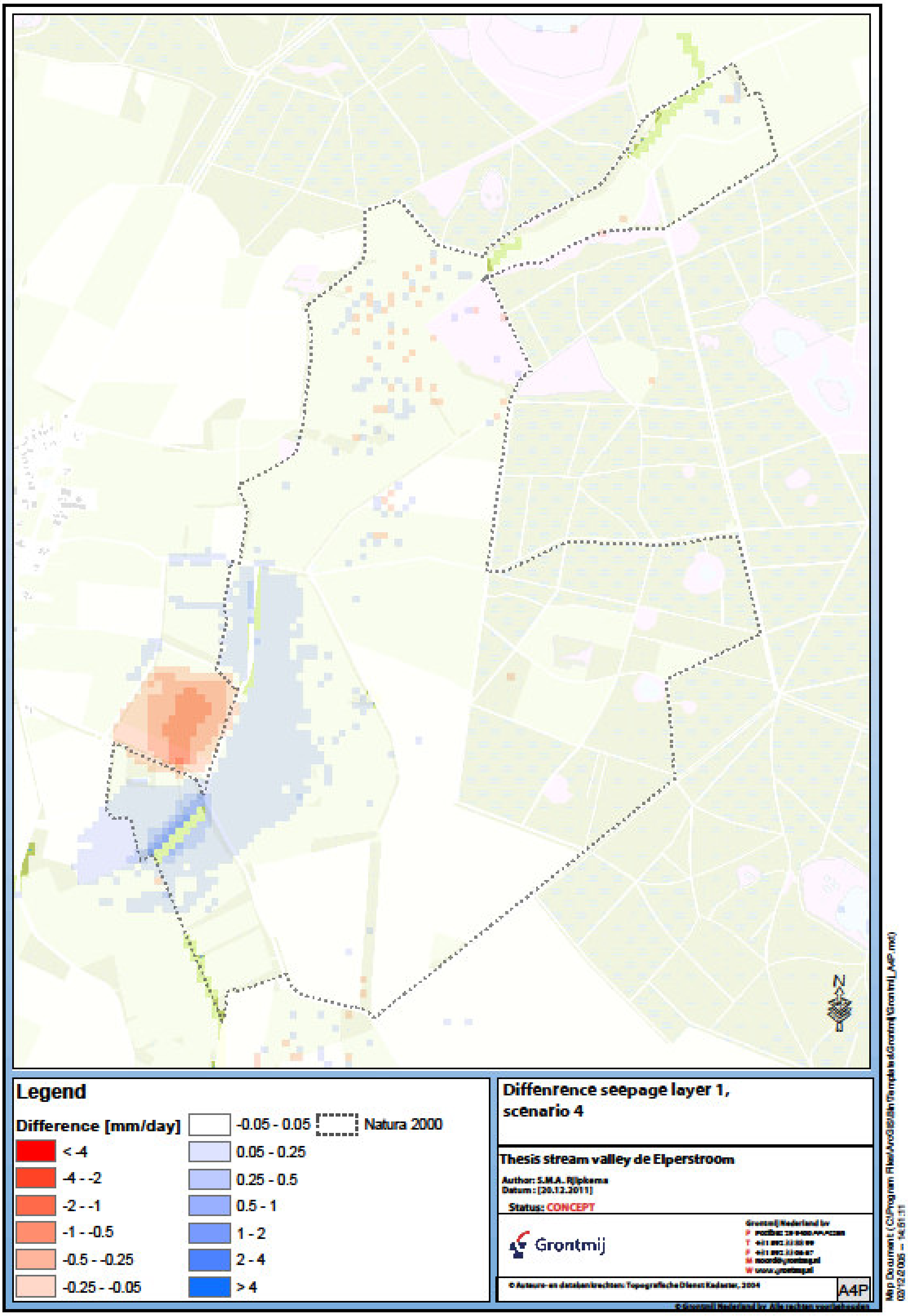
VI 74 Difference head layer 4, scenario 4.



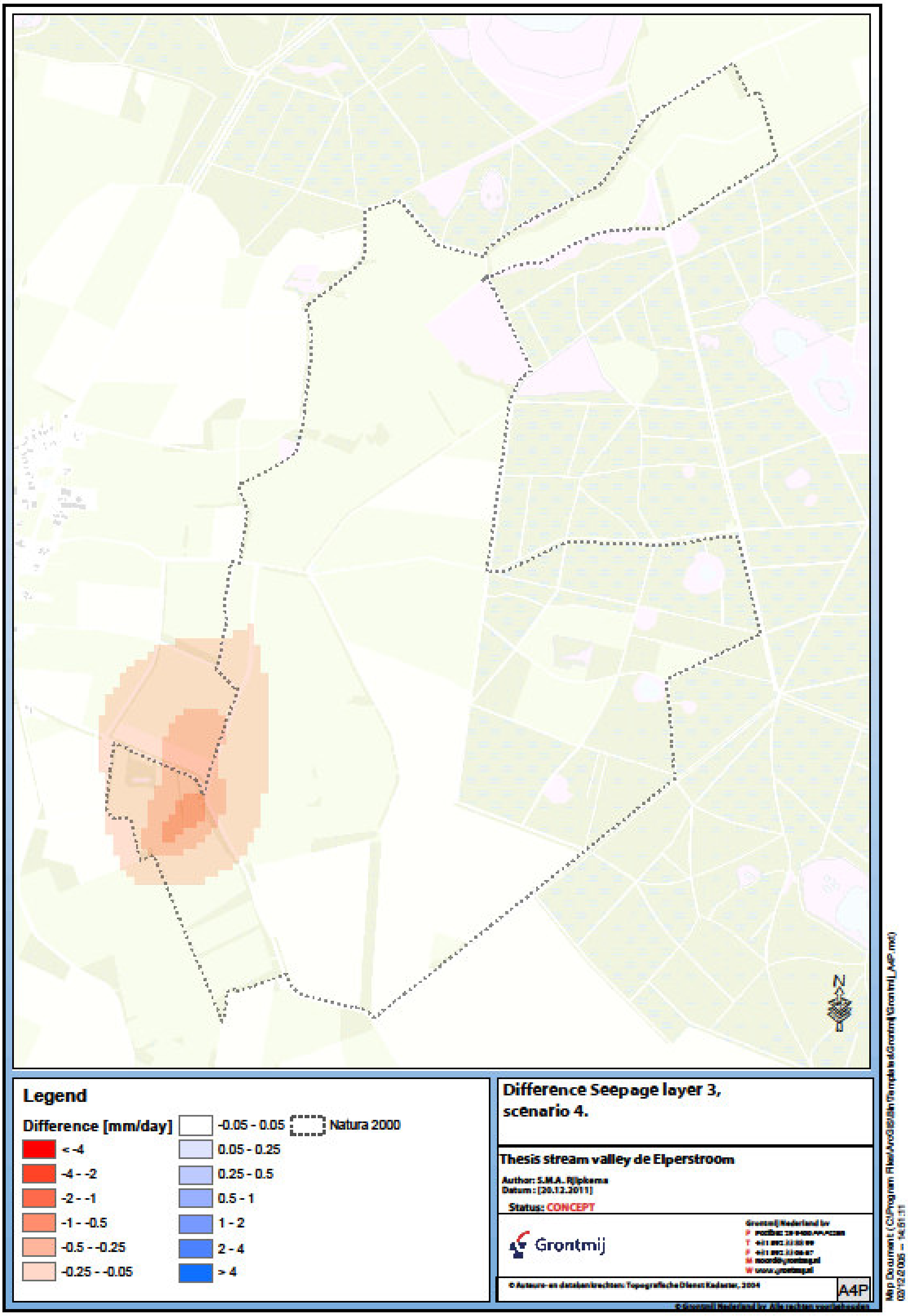
VI 75 Difference mean highest groundwater level, scenario 4.



VI 76 Difference mean lowest groundwater level, scenario 4.



VI 77 Difference seepage to layer 1, scenario 4.



VI 78 Difference in seepage to layer 3, scenario 4.