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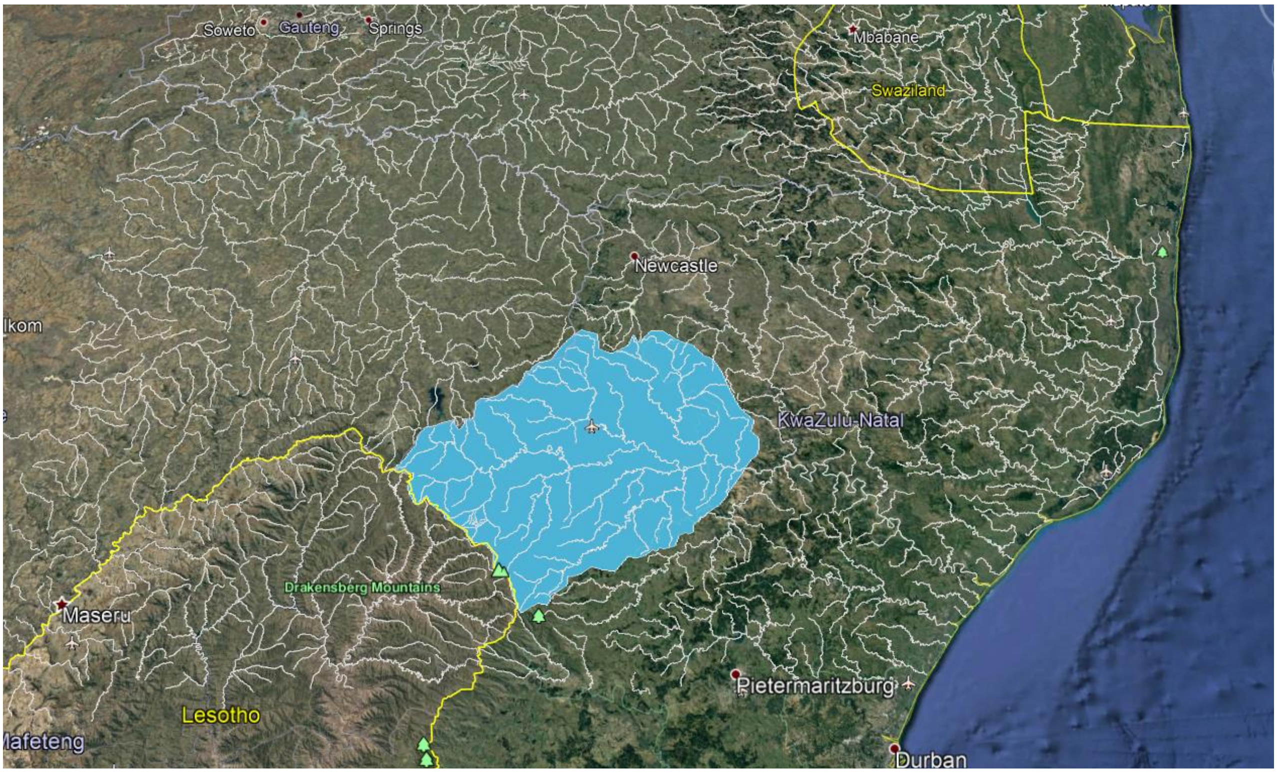
MODEL REPORT

CASE STUDY ON INTEGRATED HYDROLOGICAL MODELLING - LADYSMITH, SOUTH AFRICA



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MODEL REPORT
CASE STUDY ON INTEGRATED HYDROLOGICAL MODELLING - LADYSMITH, SOUTH AFRICA

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Approved by	**Jan Kürstein**
Description	**Report describing hydrological model for Ladysmith Area**

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CONTENTS

1. MODEL SYSTEM

The model project is a part of the SSC program between Denmark and South Africa on the water track. The groundwater model is established in connection with a 3D geological model /4/ making the geological input to the model. The model system is established based on the danish groundwater mapping methodology where 3D geological models and groundwater models make the basis for delineation of groundwater catchment areas, groundwater protection areas and calculation of sustainable abstraction from the aquifers. In Denmark we delineate catchment areas based on models with a 100 meters grid and performance criteria's corresponding to a detail model after danish performance standards /5/ (or as close as possible). It will be investigated whether these standards are adoptable to South Africa or they must be modified.

In Denmark the most common used model systems is Modflow and Mike She. When using Modflow usually the groundwater recharge is extracted from a regional Mike She Model. The model system used in this project is MIKE SHE /4/. MIKE SHE is not only a groundwater model, but an integrated hydrological software tool that covers the whole water cycle on land, as shown in Figure 1, and integrates different packages each describing:

-the root zone, EP package
-overland flow, OL package
-the unsaturated zone, UZ package
-the saturated zone, SZ package
-flow in rivers and lakes, MIKE 11 (or MIKE HYDRO RIVER)

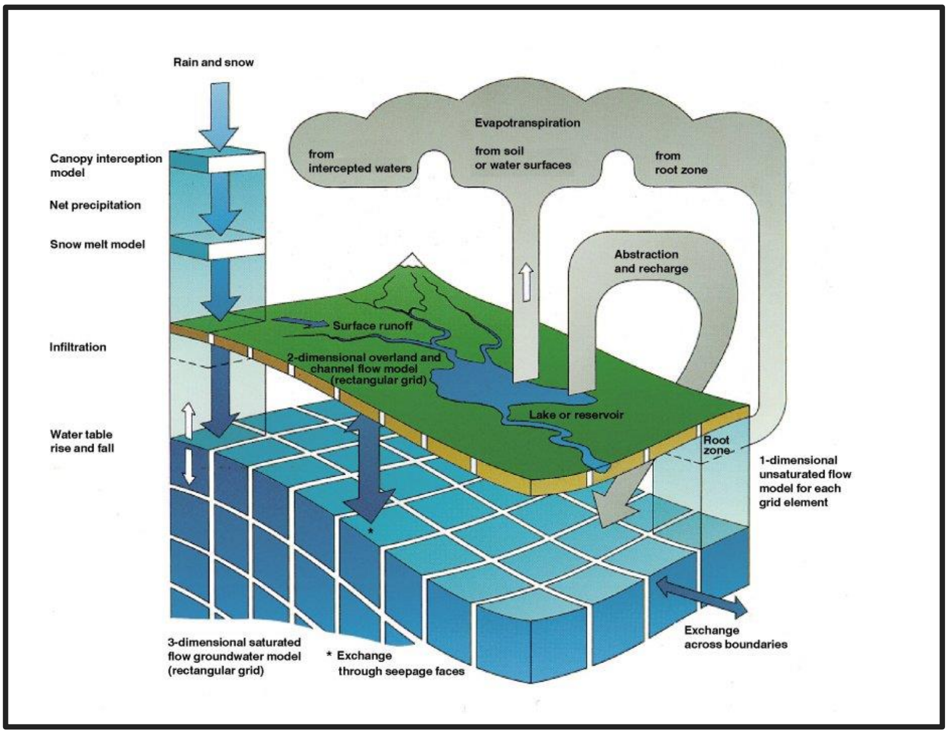


Figure 1 The mode system – MIKE SHE

The advantage using the integrated approach in MIKE SHE is that the net precipitation is calculated as a part of the modelling process, so it is not necessary to calculate it prior to the modelling. Using this approach reduce the uncertainties in the calculation of the groundwater recharge and is very suitable in semi-arid climates with high evaporation and changes between wet and dry seasons.

2. GROUNDWATER MODEL TYPES

The model area covers the uThukela District Municipality (DM), which is one of ten district municipalities within the KwaZulu-Natal Province. The area is dominated by rural settlements with a low-density population of 58 persons per km^2. The low-density rural settlement constitutes a problem for providing services in a sustainable manner in terms of operational and maintenance costs. However, several communities consist of villages, making it easier to provide services in these areas, and utilizing the local available groundwater resource will probably make the water supply more economic sustainable and more climate resilient.

Therefore, a groundwater resource assessment and development plan within the district has been initiated and the groundwater models developed in the present project shall support how much groundwater there can be abstracted sustainably within the area.

The model system has been established with 3 levels of models, from regional to local scale, the larger regional model provides flow boundaries to the local model, and the local model to give flow boundaries to the detail model. The used grid resolutions are shown Table 1. The purpose of the regional model has mainly been to give flow boundaries to the local model which has been used for the main purposes with the models – delineating catchment areas and calculation of sustainable yields. The detail model has been used to validate the model on independent data in a local area and to investigate the benefit of a finer model grid resolution.

The grid size for the local model have been limited by very large model areas combined with more than 20 computational layers, needed to resolve the 3D hydro stratigraphical voxel model, which require very large computer power to perform the simulations. It was not possible to make the model in a 100-meter grid which are used to delineate catchment areas in Denmark. But recommended grid sizes for future modelling depends on the actual purpose of the model versus the hydrogeological situation.

Model type	Used gridsize (m)	Area (km2)
Regional model	400	12990
Local model	250	6424
Detail model	67.5	401

Table 1 Used grid sizes and area of the models

The model areas are shown on Figure 2.

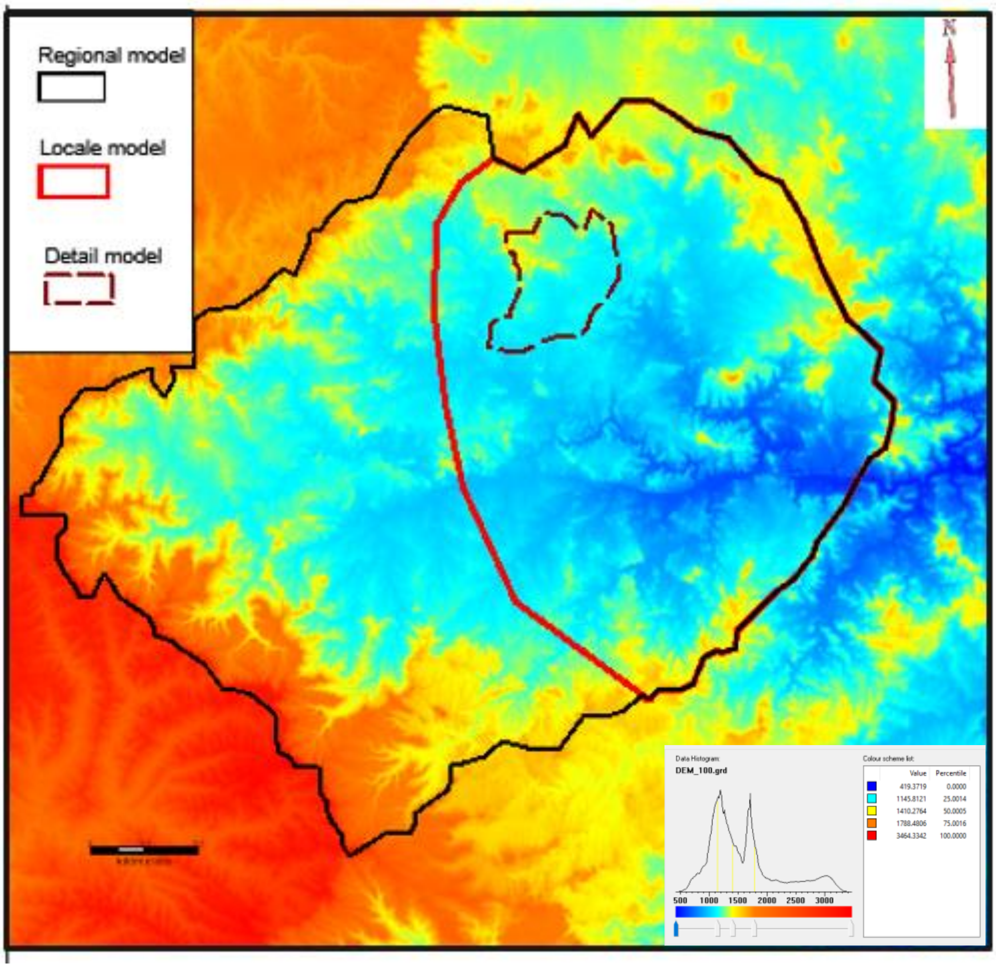


Figure 2 Model areas. The background is the topography with signature shown in down right corner

The regional model covers the whole river basin upstream Ladysmith reaching the Drakensberg mountains towards south west. The area of the regional model is 12.990 km^2 and has been delineated mainly from the topography. The elevation is more than 3000 meters above sea level in the south west end and around 500 meters above sea level in the most downstream eastern end.

The local model covers the target areas for Umgeni Water and has an area of 6424 km^2 and the local model 401 km^2.

3. DATA

To construct the hydrological model, data were received from Department of Water and Sanitation (DWS) and from Umgeni water. The following data were received:

Data received from Department of water and Sanitation, DWS

-Daily measurements of precipitation for the period 2005-2019
-Daily measurements of potential evaporation for the period 2005-2019
-Land use theme
-Transmissivity maps
-Borehole yield from blow test
-Evaporation maps
-Groundwater potential heads measurements from boreholes
-River discharge measurements
-Depth to water strikes in individual boreholes
-Licensed groundwater abstractions from the Warm database*
-Towns, Communities and Cadastral

*The Warm database is a national database where water use licenses are stored.

Data received from Umgeni Water

-Borehole geological and construction logs inclusive depth to water strikes
-Water resource and water demand reports
-GIS maps of:
    -Hydro census
    -Water reservoirs
    -Rivers and dams
    -Urbanized areas and communities
    -Water bulk pipelines
    -Water treatment plants
    -Reticulation systems
    -Primary and secondary groundwater targets for Umgeni Water

The different datatypes are more detailed described in the following sections.

3.1 Current water supply system

The current water supply system is shown in Figure 3. Water transferring pipelines exists around towns and local communities. The primary source of water is surface water and several of the pipelines originate from dams, from where water is transported to local water treatment plants and reservoirs and distributed further in reticulation systems. Figure 4 provides a zoom in on the system at Ladysmith, where it can be seen that a part of the water supply originates from a dam located southwest of the city.

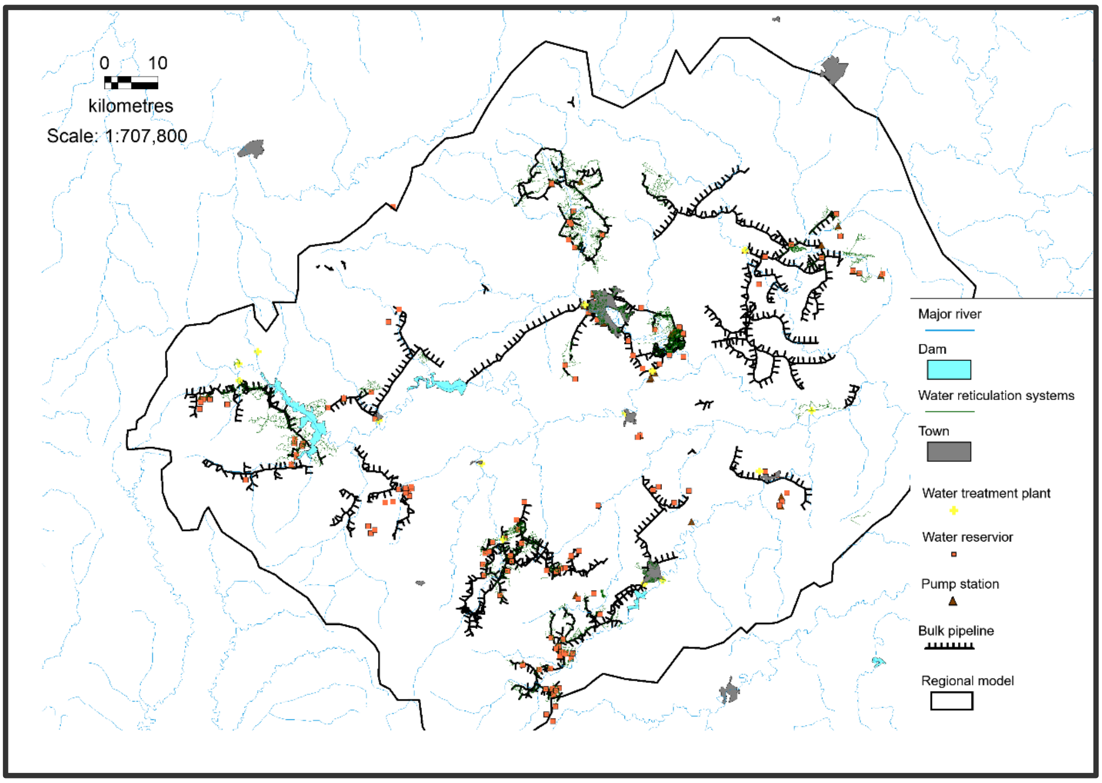


Figure 3 Current water supply system

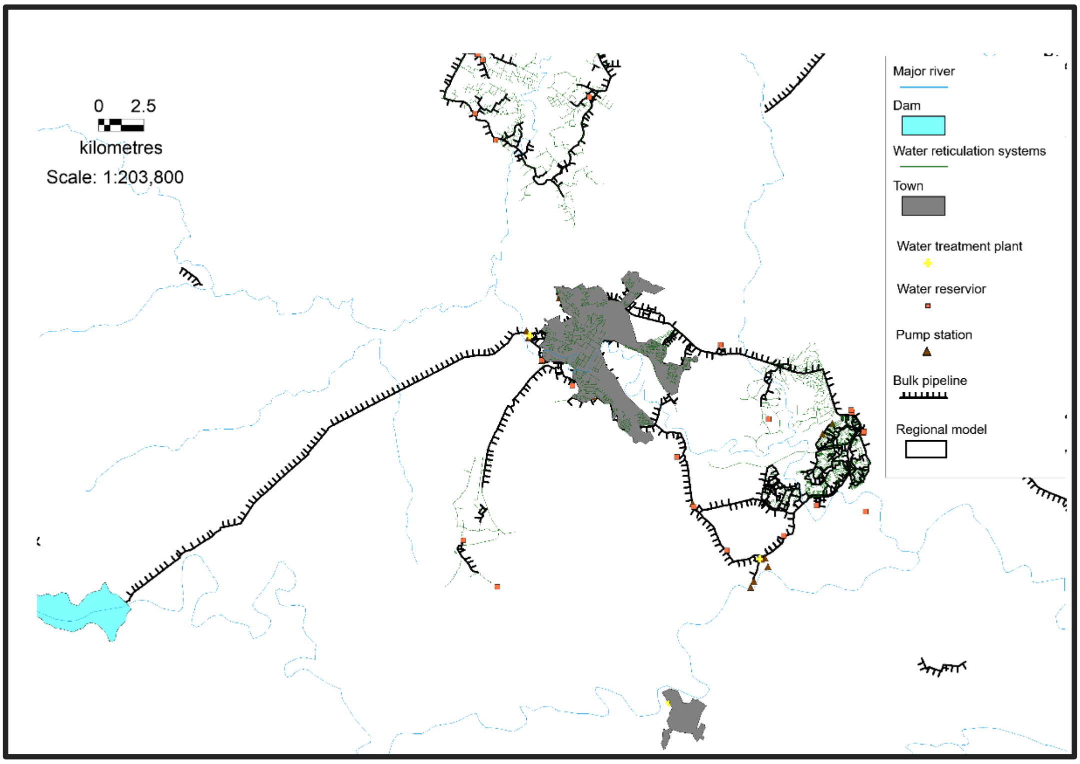


Figure 4 Current water supply system around Ladysmith

3.2 Hydrological data and groundwater data

Available hydrological and groundwater data are shown on **Error! Reference source not found.**. As it can be seen from the figure there are many boreholes in the area. At the groundwater sites timeseries of groundwater heads have been available.

Selected observed groundwater heads and surface water sites with discharge measurements, has been used for calibration of the model.

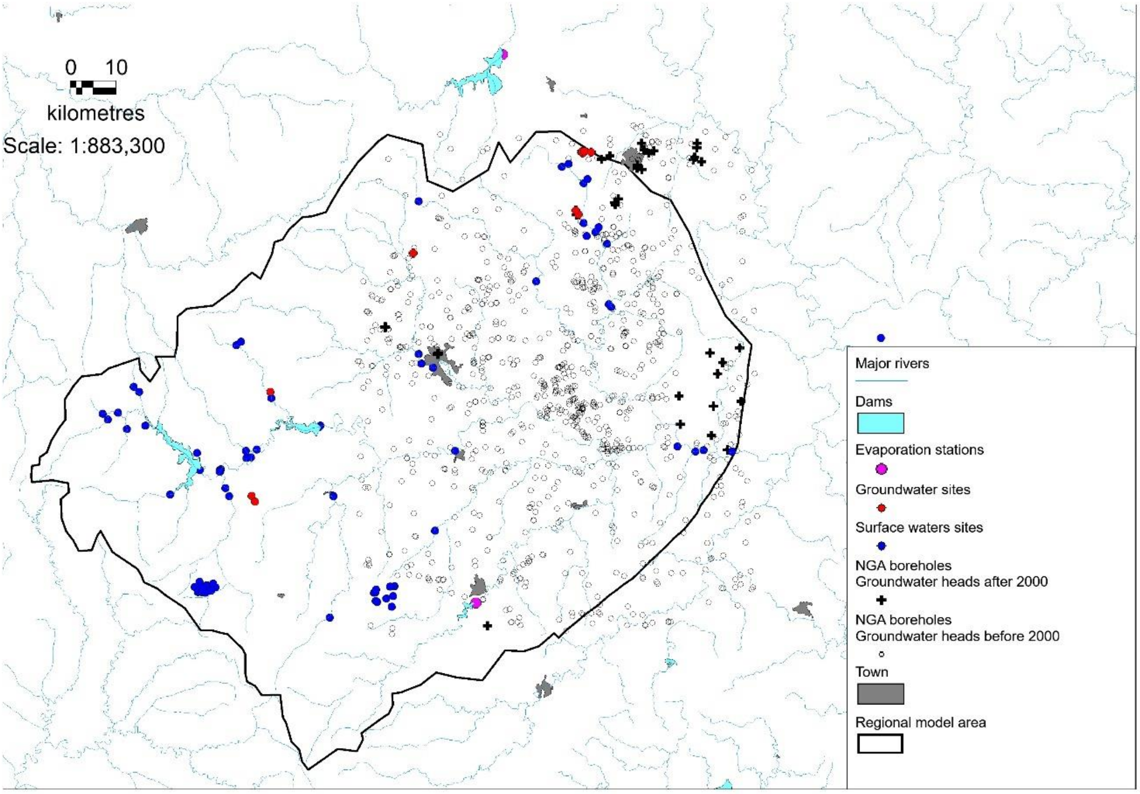


Figure 5 Hydrological data and groundwater data

Most of the screens and related water strikes are located within the upper 100 meters below ground surface as it can be seen on Figure 6. There are almost 1000 measurements of the groundwater table within the area but most observations are of older data as it can be seen on Figure 7. Particularly in the period 1950-1975 there are many measurements. Older groundwater head measurements have also been used in the optimization of the model, to contribute in areas that otherwise would lack groundwater heads measurements.

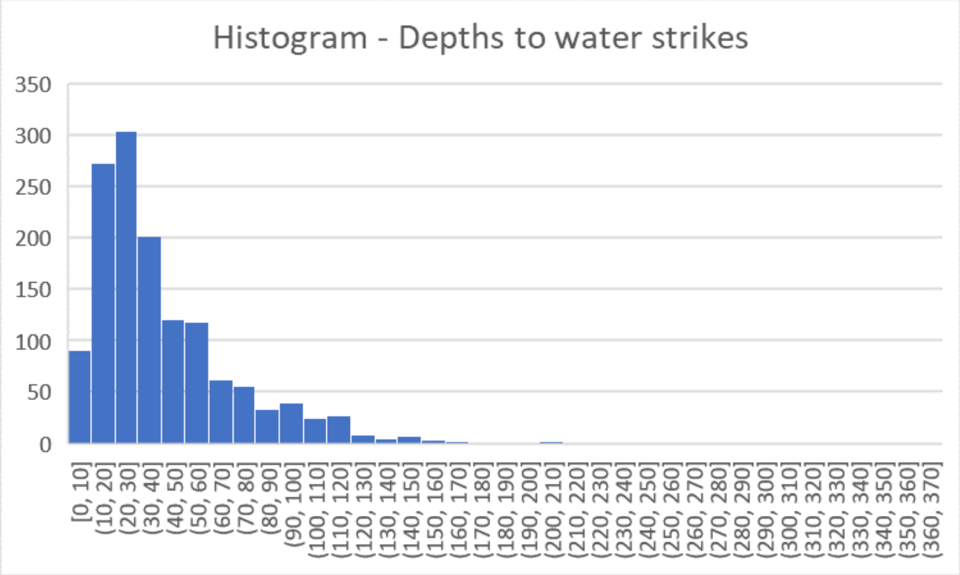


Figure 6 Histogram over depth to screen/water strike

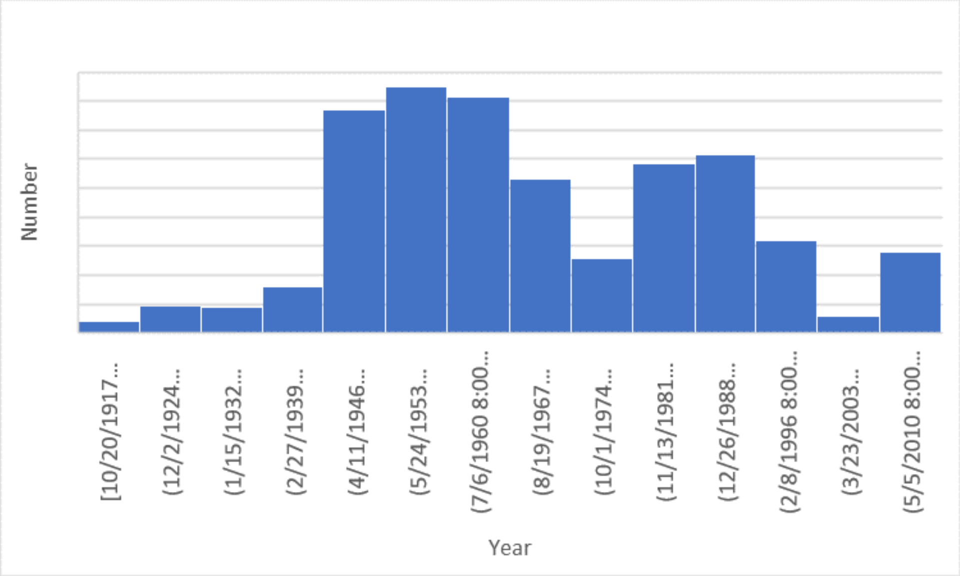


Figure 7 Histogram over age over groundwater measurements

3.3 Current groundwater abstraction

The current groundwater abstraction taking place in the area is primarily from private boreholes with a registered license. Schedule 1 water, which does not require a license, is assumed not to be significant in the area, and is not implemented in the model except those included in the WARM database. A water use license is required if the daily water abstraction is more than 10 m^3. Water abstractions below 10 m^3 per day is called schedule 1 abstractions.

The current abstraction is shown on Figure 8. Within the local model area, the current groundwater abstraction is not very high, approximately 20 wells with some of the wells located at the boundary between the local and regional model. It is the permits that is implemented in the models (both regional and local), and for most of the wells it is below 25.000 m^3/year.

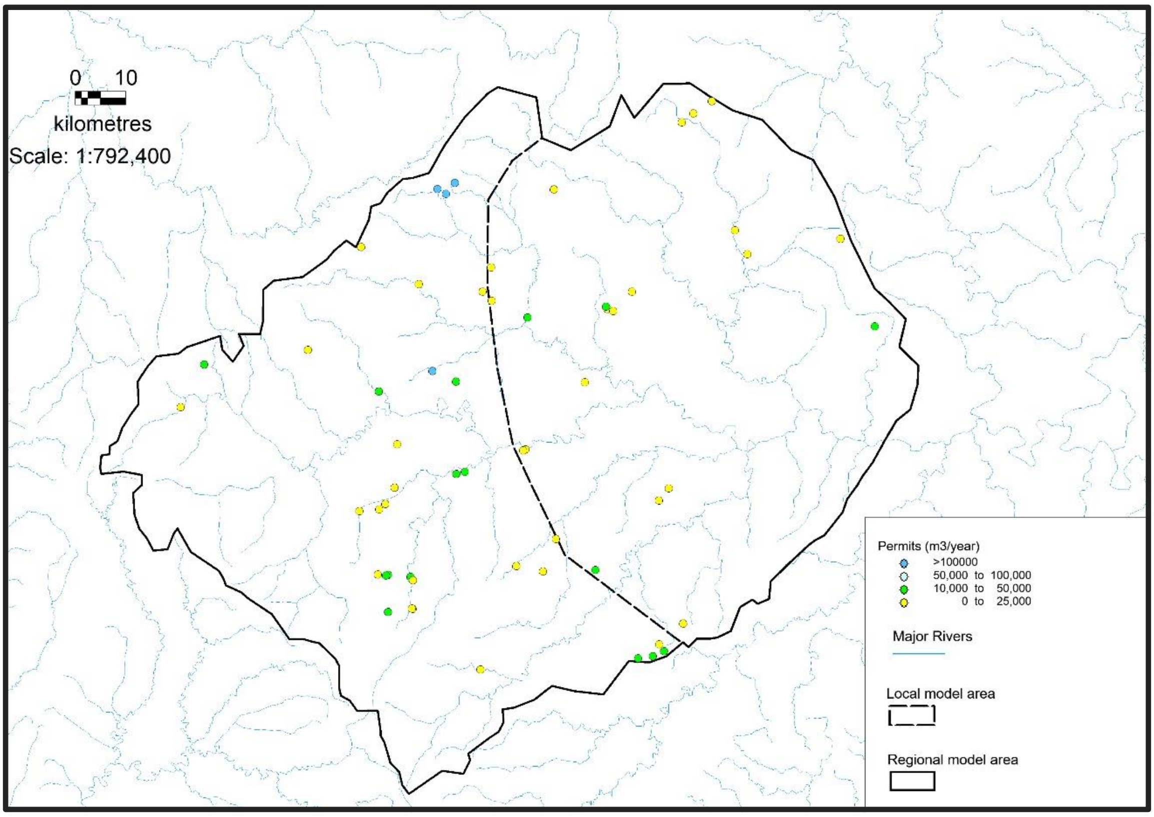


Figure 8 Licensed groundwater abstraction

3.4 Aquifer yield

For many boreholes the aquifer yield has been assessed from blow yield, Figure 9. Blow yield is not as accurate as test pumps but can give an indication of the aquifer yield while drilling or air flushing. It appears that based on blow yields the aquifer yield have a significant variation within the area. In many boreholes' values below 1 m^3/hours is found, indicating a low yield. However, values below 1 m^3/hour is generally considered more unreliable. Due to the large varitaiont in the area, values above 1 m^3/hour are also found in many boreholes indicating a better basis for groundwater development.

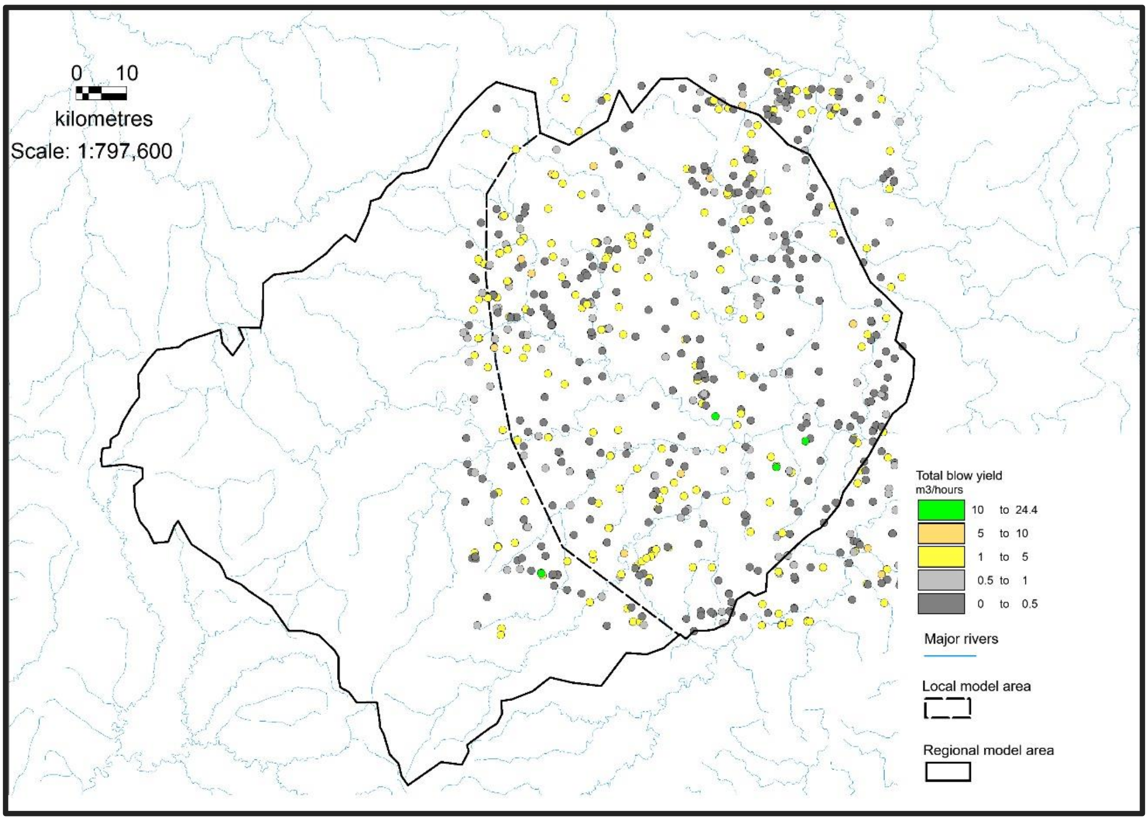


Figure 9 Total blow yield

3.5 Primary and secondary targets

Umgeni Water has defined primary and secondary targets for potential future groundwater abstractions shown in Figure 10. As can be seen, the targets have been placed near the current distribution system and local settlements, where it more easily can be implemented in the local water supply. Moreover, it appears that the targets are located near fault lines, where it is expected that the groundwater recharge will be higher and therefore the potential for groundwater development also higher.

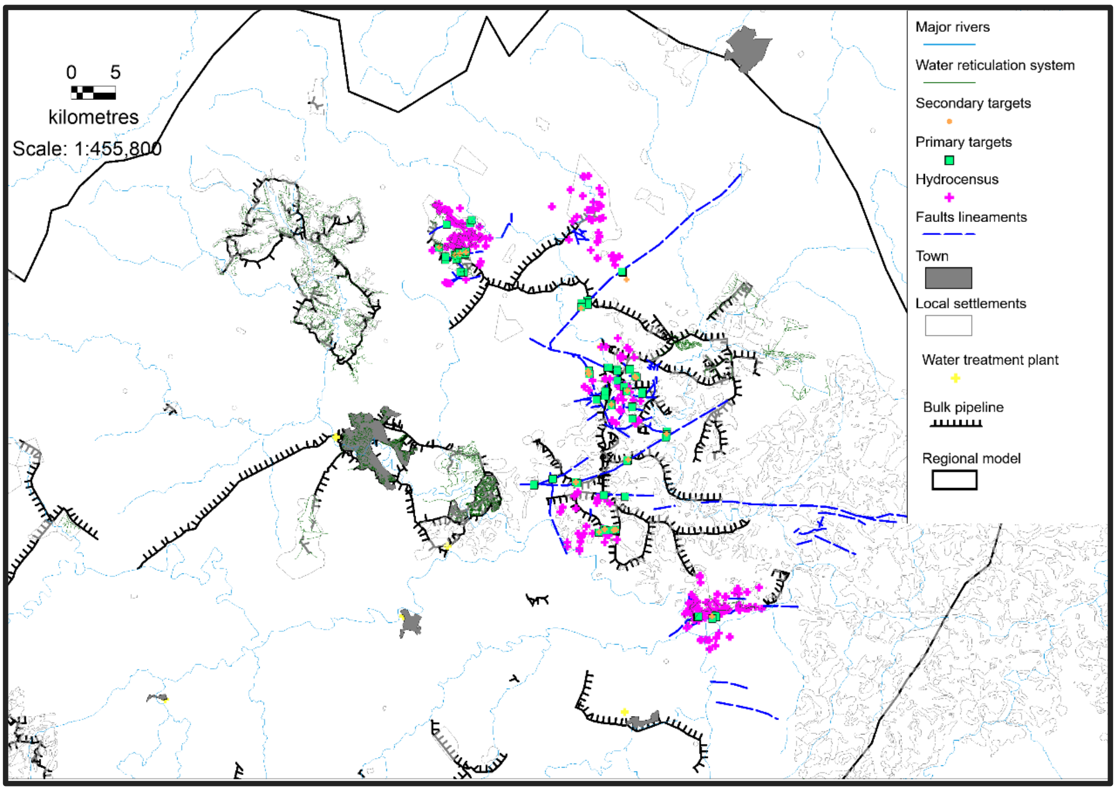


Figure 10 Primary and secondary targets

4. CALCULATION OF NET PRECIPITATION

One of the model challenges is always calculation of the net precipitation. Because of the climatic conditions in South Africa, changing between wet and dry seasons, an integrated model approach has been used to calculate the net precipitation. By using this method, the net precipitation is calculated as a part of the modelling process and not as stand-alone process. Moreover, the net-precipitation is calculated on daily basis for more than a decade, which means that the average net-precipitation can be extracted for use in steady-state models.

The daily net-precipitation has been calculated based on the data listed below:

1. Daily measurements of precipitation
2. Daily measurements of potential evaporation
3. Land use data

Daily measurements of precipitation have been received from a station located at Ladysmith and included in the hydrological model. In Figure 11 the precipitation values are shown as monthly data. The period from January to June is the wettest season and the period from September to December is in contrary very dry. The average precipitation is 574 mm/year ranging from approximately 300 mm/year to almost 800 mm/year.

According to /1/ there is a relationship between elevation and the amount of precipitation with the highest precipitation in the higher elevated areas. This has not been included in this model project but the importance is recommended to be investigated in the future.

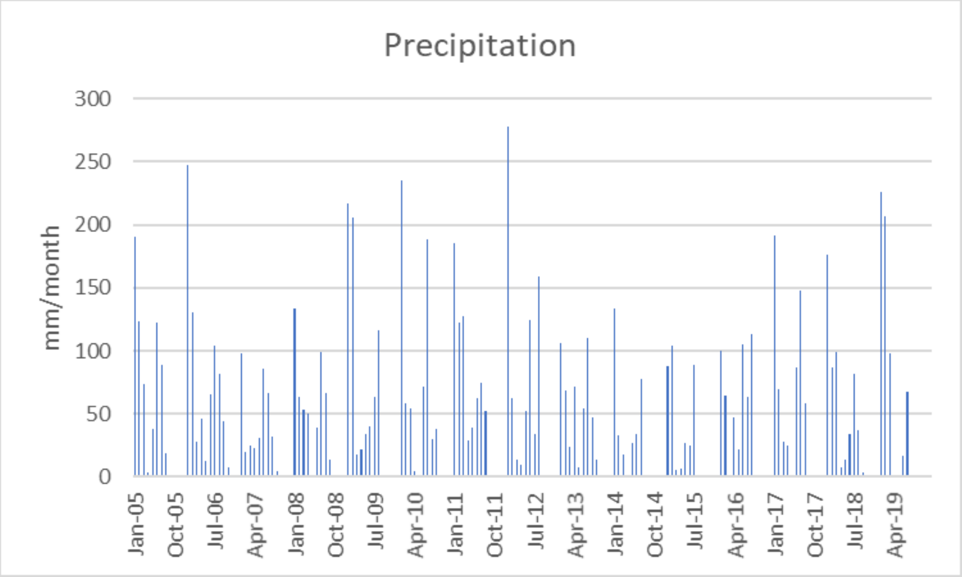


Figure 11 Monthly values of precipitation for the period 2005-2019

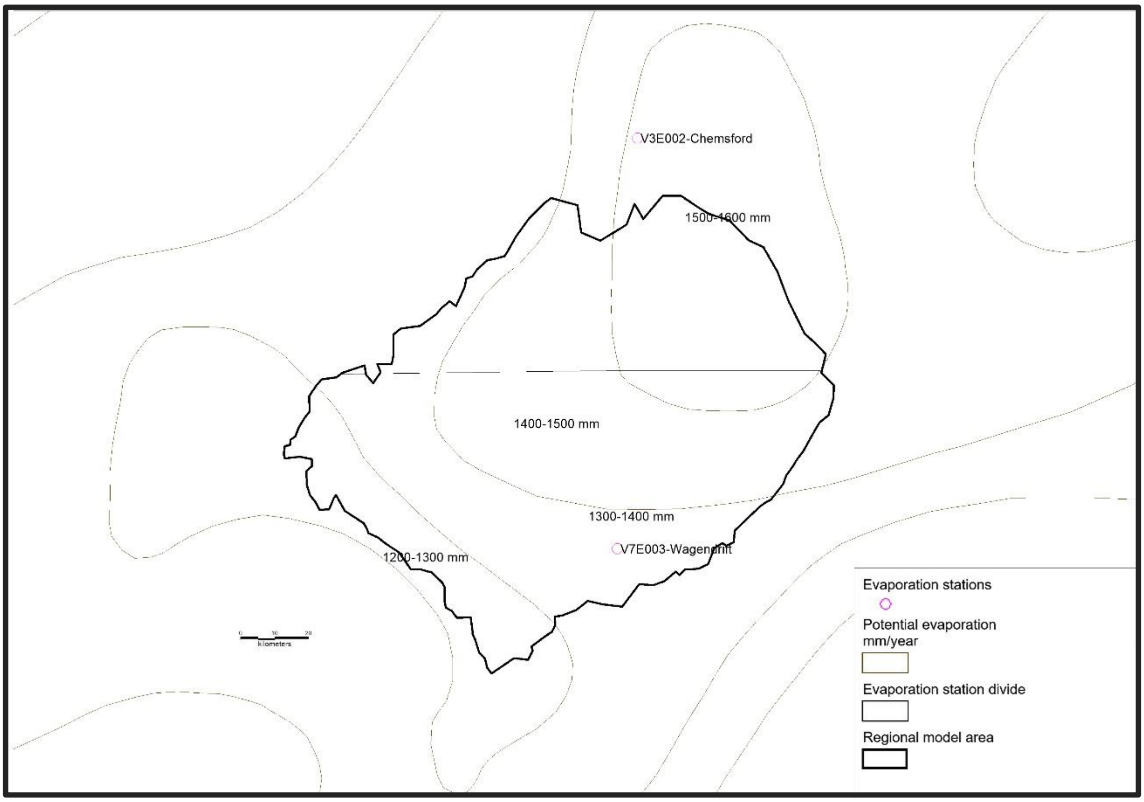


Figure 12 Location of climatic stations

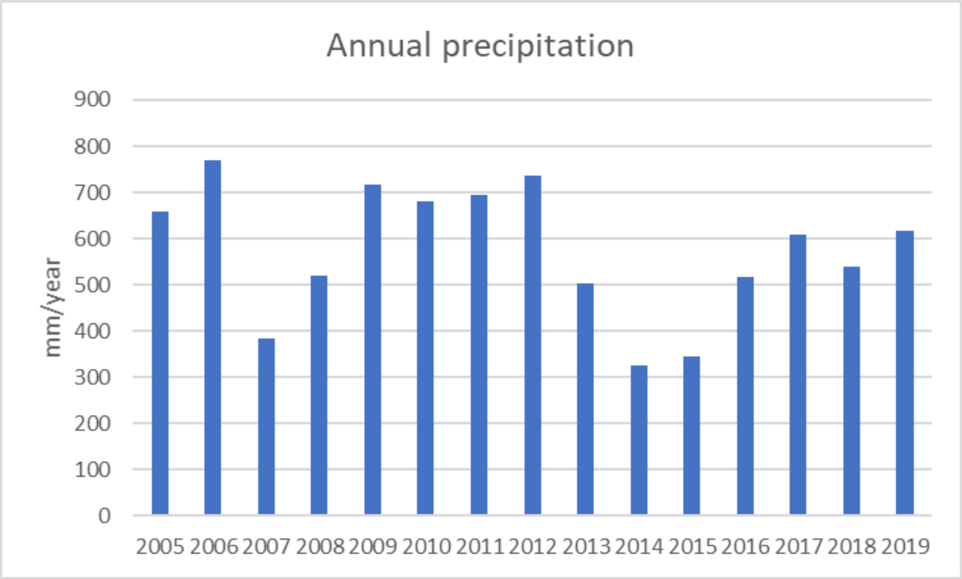


Figure 13 Annual precipitation

Data for potential evaporation on daily basis has been available from two stations, one within the model area the other a little north of the model area as it can be seen from Figure 12. Station V7E003-Wagendrift is located within the regional model area and just outside the locale model area. Station V3E002-Chemsford is located approximately 22 km north of the model area. Monthly and annually values for Station V7E003-Wagendrift are shown at Figure 14 and Figure 15, respectively. The annual average potential evaporation is 1775 mm at Station V7E003-Wagendrift and 100 mm higher at Station V3E002-Chemsford. This is not totally in agreement with the mapped potential evaporation also shown on Figure 12, where the potential evaporation is lower in higher elevated areas due to lower temperatures, but it is assumed to be local uncertainties.

The potential evaporation is included in the hydrological model on daily basis, and data from both stations are included based on Thiessen polygons.

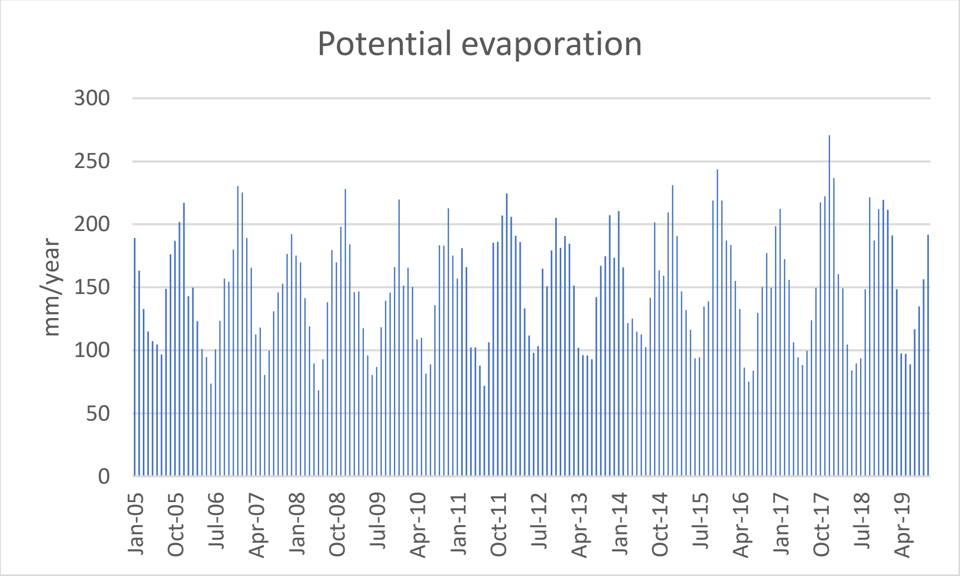


Figure 14 Potential evaporation at Station V7E003-Wagendrift, monthly values

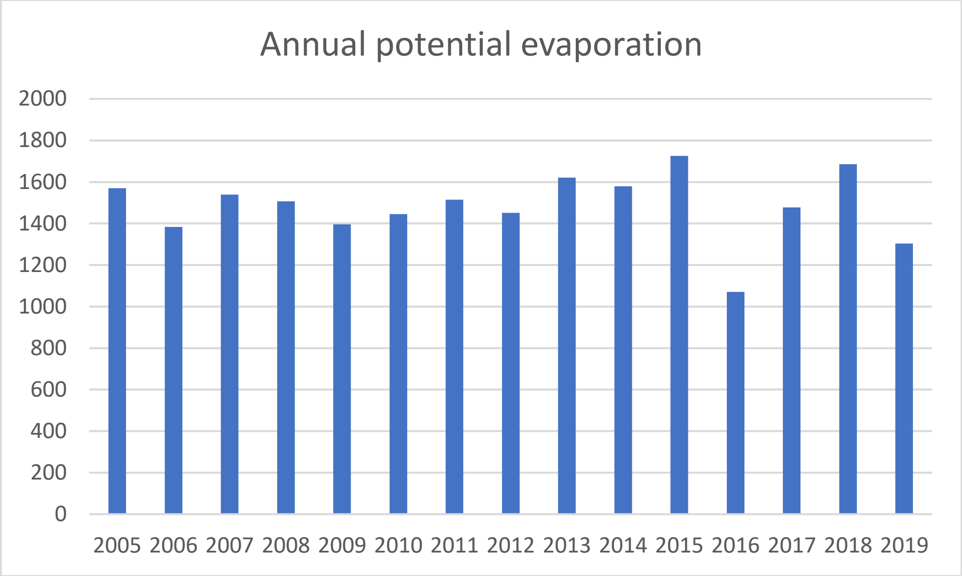


Figure 15 Annual potential evaporation at Station V7E003-Wagendrift

The actual evaporation in the model is calculated using the input from precipitation, potential evaporation, and vegetation parameters. For the distribution of vegetation parameters, the area has been divided into four land use areas; rural areas dominated by savannah, urban areas, communities, and nature areas. Each land use area is represented by the dominant crop. For both the rural areas and communities, grass has been selected as the dominant crop. For the urban areas a vegetation with a smaller leaf area index and root depth (typical for urban areas) has been selected due to the larger degree of paved areas.

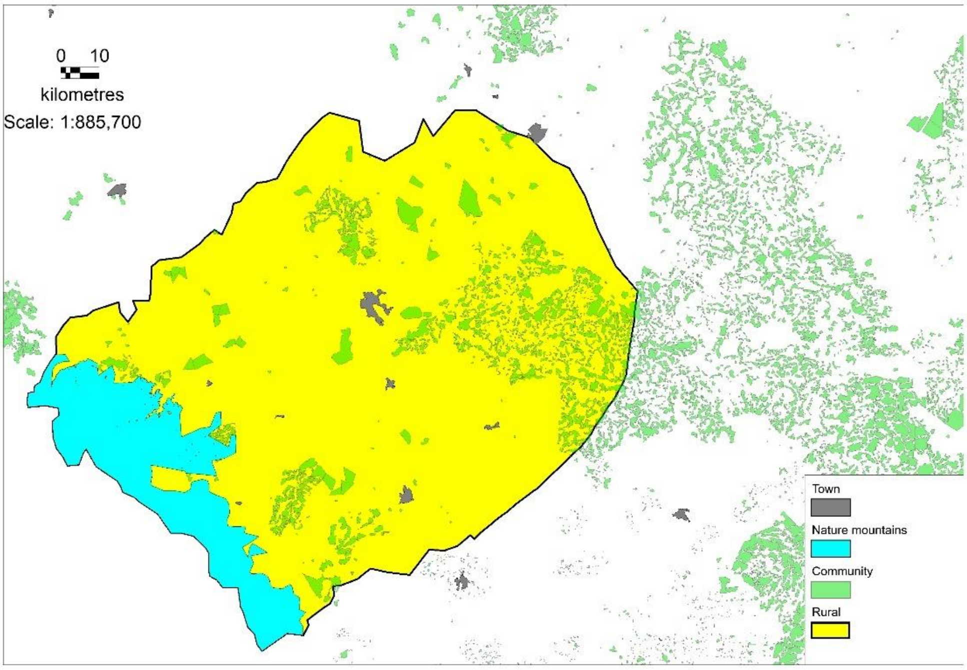


Figure 16 Land use theme used for both regional and locale model

5. REGIONAL MODEL

The purpose of the regional model is to deliver boundary conditions for the local and detailed models and to deliver some overall water balance estimations for the whole watershed. The boundary of the regional model area is shown at **Error! Reference source not found.**. The area o f the regional model is 12.990 km^2 stretching from the mountains in south west towards north east incorporating the Ladysmith area.

The grid size of the regional model is 400 meters and it has 4 layers. The simulation period is 2005-2019 with a time step on 24 hours in the saturated zone.

5.1 Topography and rivers

The Thukela River is the main river within the area. The Thukela River rises in the Drakensberg mountains and meanders through central KwaZulu-Natal and discharges into the Indian Ocean. The total area of the Thukela River Catchment is approximately 30.000 km^2 in extent and is the second largest in South Africa.

The regional model catchment area is in the upstream part originating in the Drakensberg mountains with elevations above 3000 meter above sea level and is shown in Figure 17.

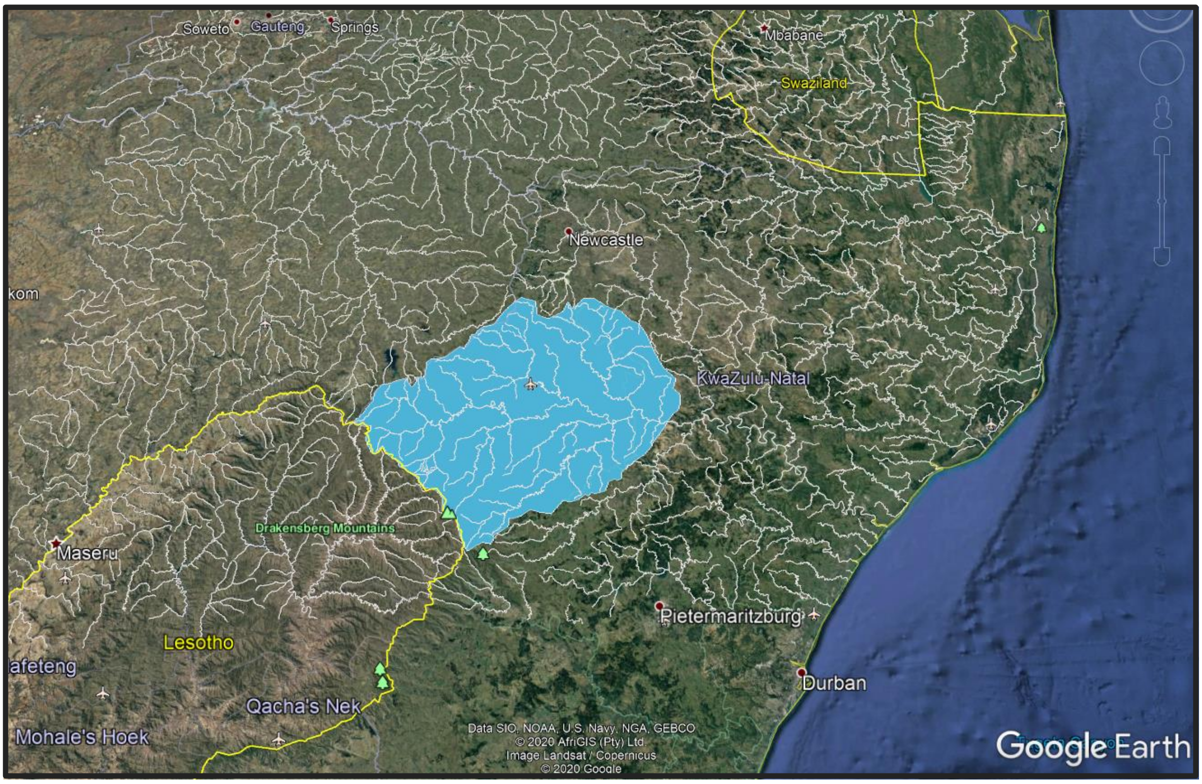
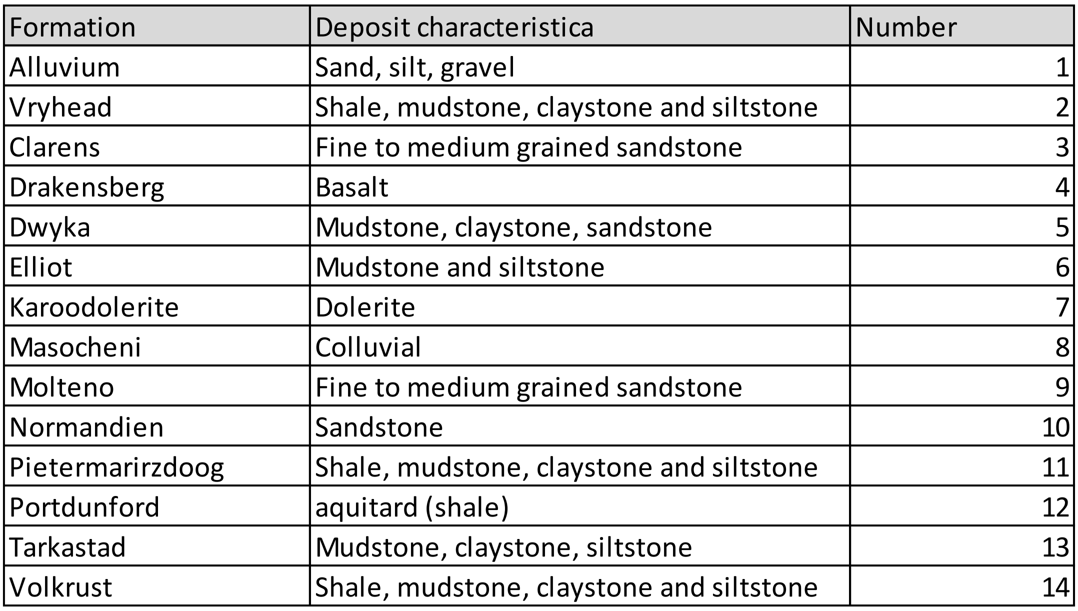


Figure 17 The regional model area

5.2 Hydrostratigraphical model

The regional numerical model consist of three geological layers with a thickness of 10 meters implemented 0-10 (Figure 18), 10-20 (Figure 19) and 20-30 meter below ground surface (Figure 20), respectively. A bottom layer with a thickness of 200 meter with the same geological distribution as 20-30 meters below ground surface has been added to the model to describe the deeper parts of the groundwater flow.

The geological interpretation consists of 14 units shown in Table 2 and the distribution on Figure 18 - Figure 20.



Formation	Deposit characteristica	Number
Alluvium	Sand, silt, gravel	1
Vryhead	Shale, mudstone, claystone and siltstone	2
Clarens	Fine to medium grained sandstone	3
Drakensberg	Basalt	4
Dwyka	Mudstone, claystone, sandstone	5
Elliot	Mudstone and siltstone	6
Karoodolerite	Dolerite	7
Masocheni	Colluvial	8
Molteno	Fine to medium grained sandstone	9
Normandien	Sandstone	10
Pietermarirzdoog	Shale, mudstone, claystone and siltstone	11
Portdunford	aquitard (shale)	12
Tarkastad	Mudstone, claystone, siltstone	13
Volkrust	Shale, mudstone, claystone and siltstone	14

Table 2 Geological units in regional model

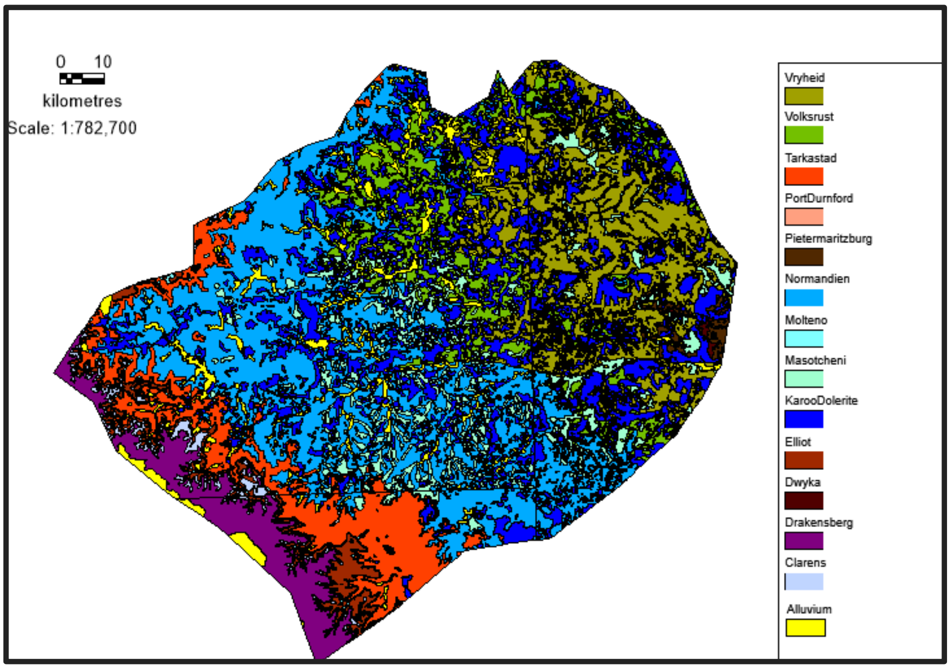


Figure 18 Geological distribution 0-10 meters below ground surface

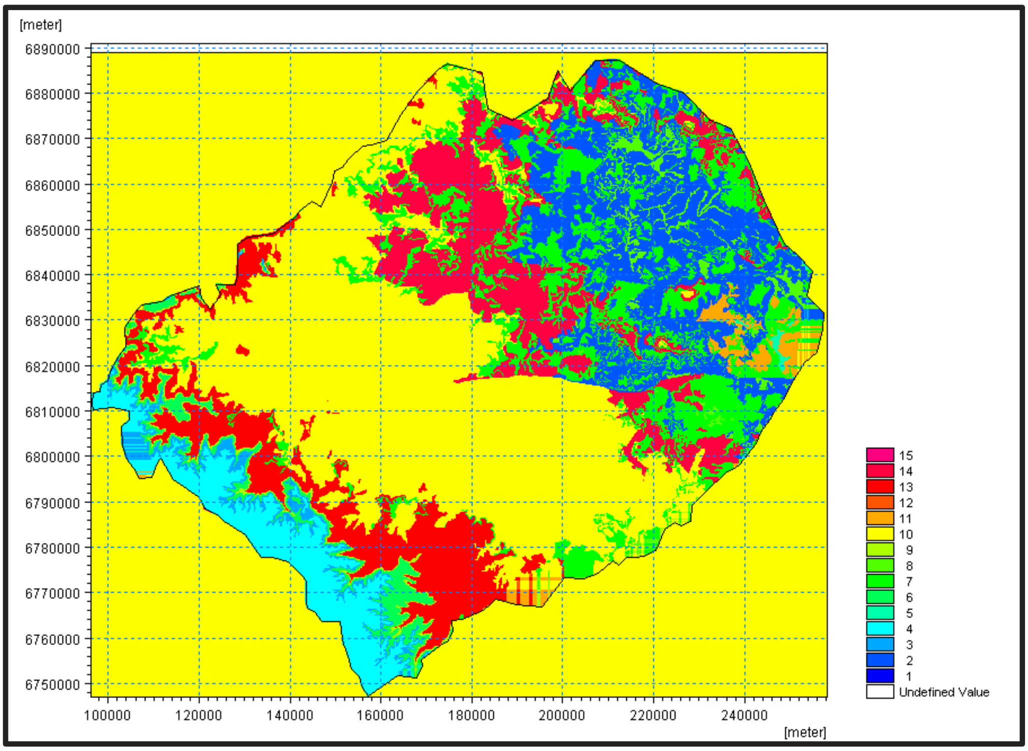


Figure 19 Geological distribution 10-20 meters below ground surface. The numbers refer to Table 2 except no 15 which is water (not present in this layer).

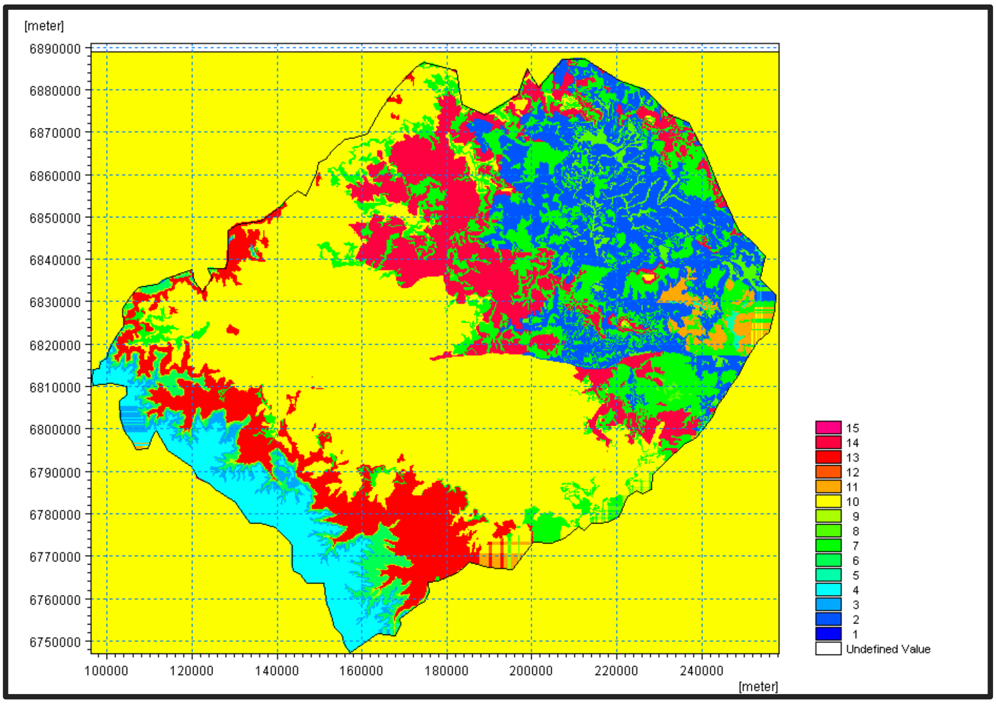


Figure 20 Geological distribution 20-30 meters below ground surface. The numbers refer to Table 2 except no 15 which is water (not present in this layer).

5.3 Boundary conditions

The outer model boundary is delineation based on topographic divides assuming these represent no-flow boundaries, except at the eastern boundary where subsurface groundwater outflow is occurring. In this area, a head boundary has been implemented. No map based on synchronous groundwater head observations is available, and the groundwater at the eastern boundary was therefore interpolated from previous measured groundwater heads in the NGA boreholes. Even though there is a great uncertainty in the interpolation (and therefore also in the head boundary), it is assumed better than just using the surface elevation. The interpolated groundwater head map is shown on Figure 21 and the distribution of measured groundwater heads are shown in **Error! Reference source not found.**. From **Error! Reference source not found.** it is seen th at the largest concentration of younger groundwater heads measurements is located near to the eastern constant head boundary, making the boundary more reliable.

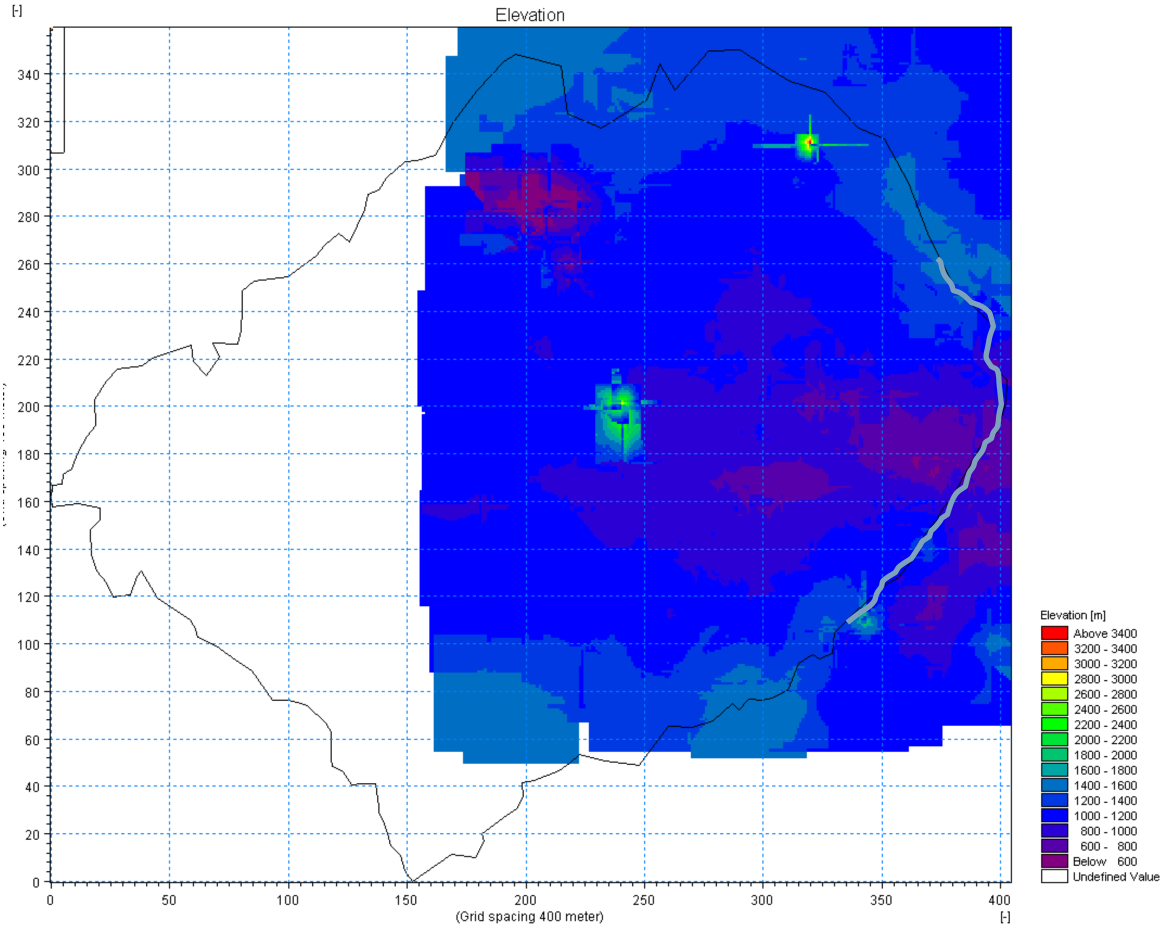


Figure 21 Interpolated groundwater head map used for the definition of the eastern head boundary. The location of the head boundary is shown with the thick line

5.4 Unsaturated zone

The unsaturated in both the regional and local models is described by the 2-layer method, which is the method used in the Danish methodology. The two-layer method is a rather simple water balance method dividing the unsaturated zone into two zones, respectively the root zone and the zone between the roots and the water table. Richards equation were also initially tested but discarded because of too long simulation times.

5.5 Rivers

The rivers shown on Figure 22 has been implemented in the model. Cross-sections were first generated automatically based on the elevation model (DEM 100x100 meter) and thereafter fitted to the model. Because of the very large model area and many rivers stretches, the cross-sections were initially generated with an equal distance on 500 meters and 75 meters wide. Afterwards the cross sections were manually updated in the upstream areas where the cross-section width are smaller. The rivers were run with kinematic router as solver which is the most stabile solver.

MIKE 11 was used to simulate the rivers, while the automatic cross sections generation were made in MIKE HYDRO RIVER. An example from Sunday River is shown on Figure 23, where the upstream cross section is 20m wide and is located at an elevation just above 1540m while the downstream section has a width of 75 at elevation approx. 1200m.

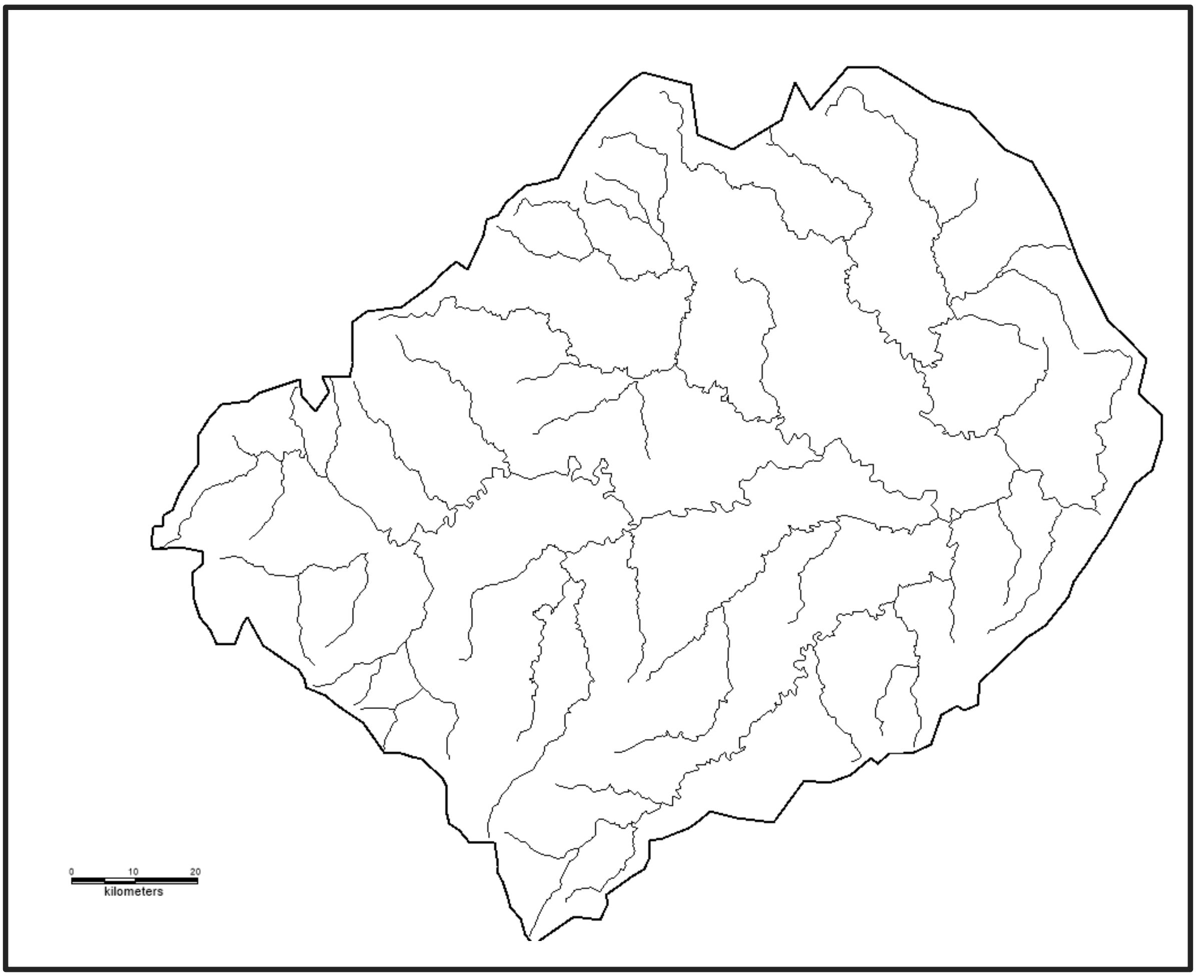


Figure 22 Implemented rivers in the model

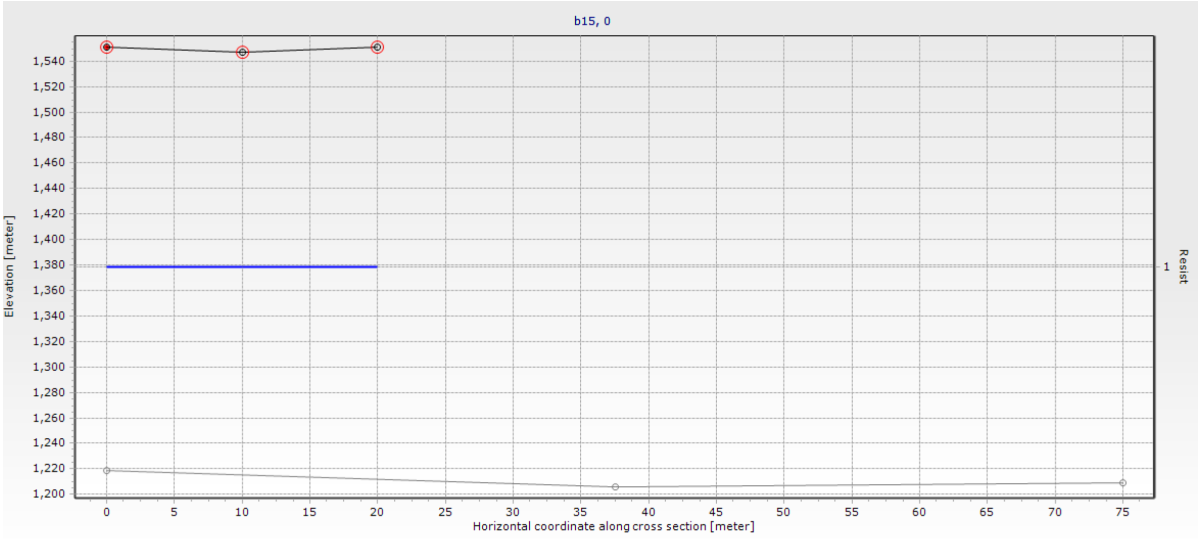


Figure 23 Example of river cross section from Sunday River (called B15 in the model)

5.6 Calibration targets

The regional model was calibrated both against groundwater and surface water.

The selected groundwater targets were Umgeni water monitoring well and the groundwater sites shown on **Error! Reference source not found.**. The calibration period was 2011-2014 and only a ctual measurements from this period were used in the optimization.

For surface water, the location of the used discharge stations is shown on Figure 24. Focus has been on discharge data from stations located near the local model boundary because of the main purpose with the regional model to create model boundaries for the local model.

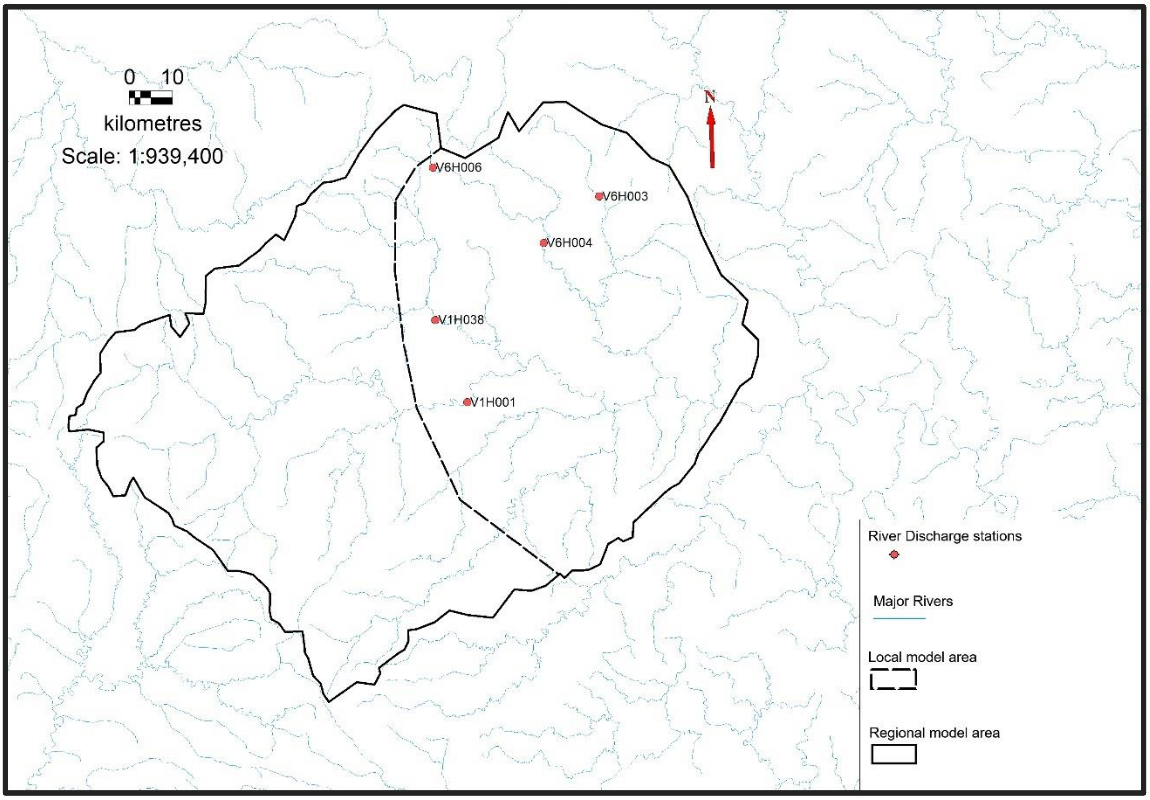


Figure 24 Surface water discharge stations

5.7 Sensitivity analysis – regional model

The optimization of the regional model started with a sensitivity analysis. The results are shown on Figure 25 and Figure 26 for groundwater heads and river discharges respectively. The results show that for groundwater heads the most sensitive parameters are the hydraulic conductivity and for the river flow other parameters as overland flow and vegetation parameters also become important. This is not unusually; the river flow is often very sensitive to surface related processes. It was more surprising that the leakage coefficient describing leakage between the surface water and groundwater, did not turn out to be sensitive. It could be because of the general low hydraulic conductivities in the area, but the exact reason hasn't been examined in more detail.

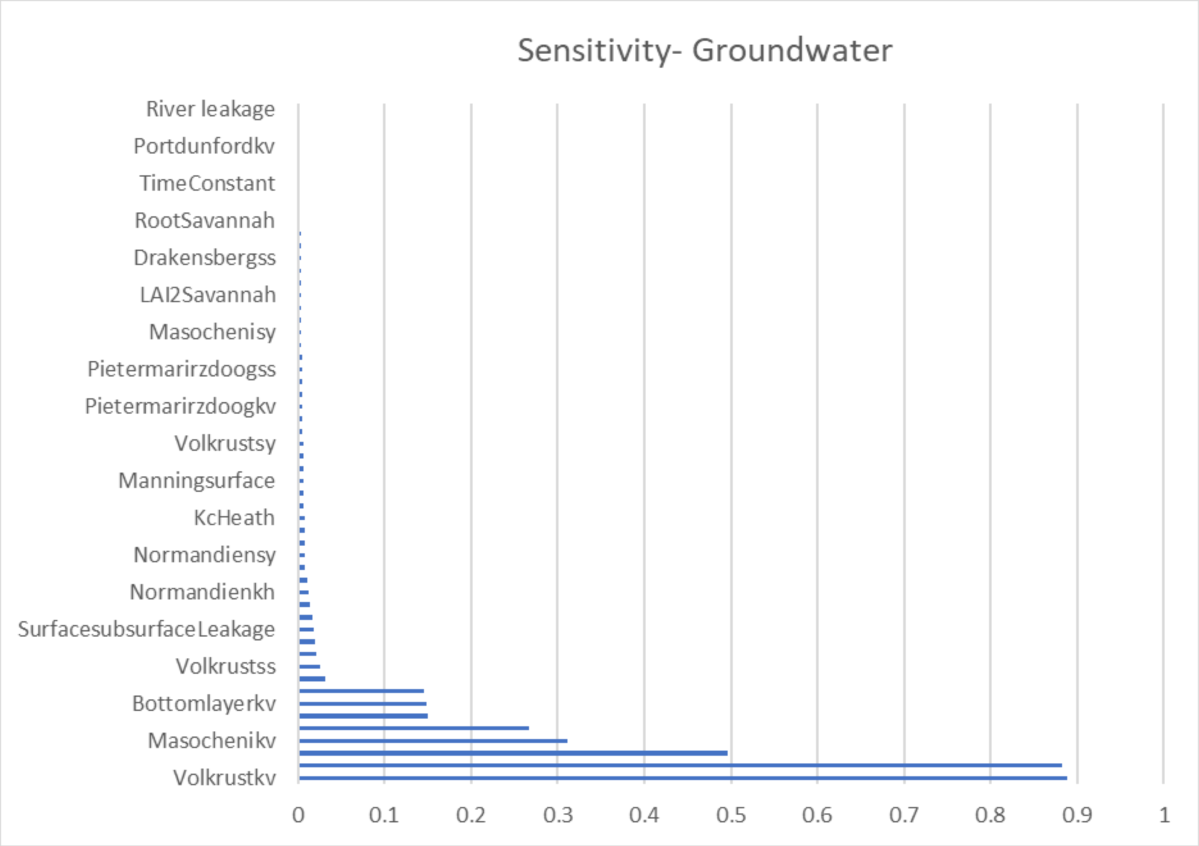


Figure 25 Sensitivity groundwater – regional model

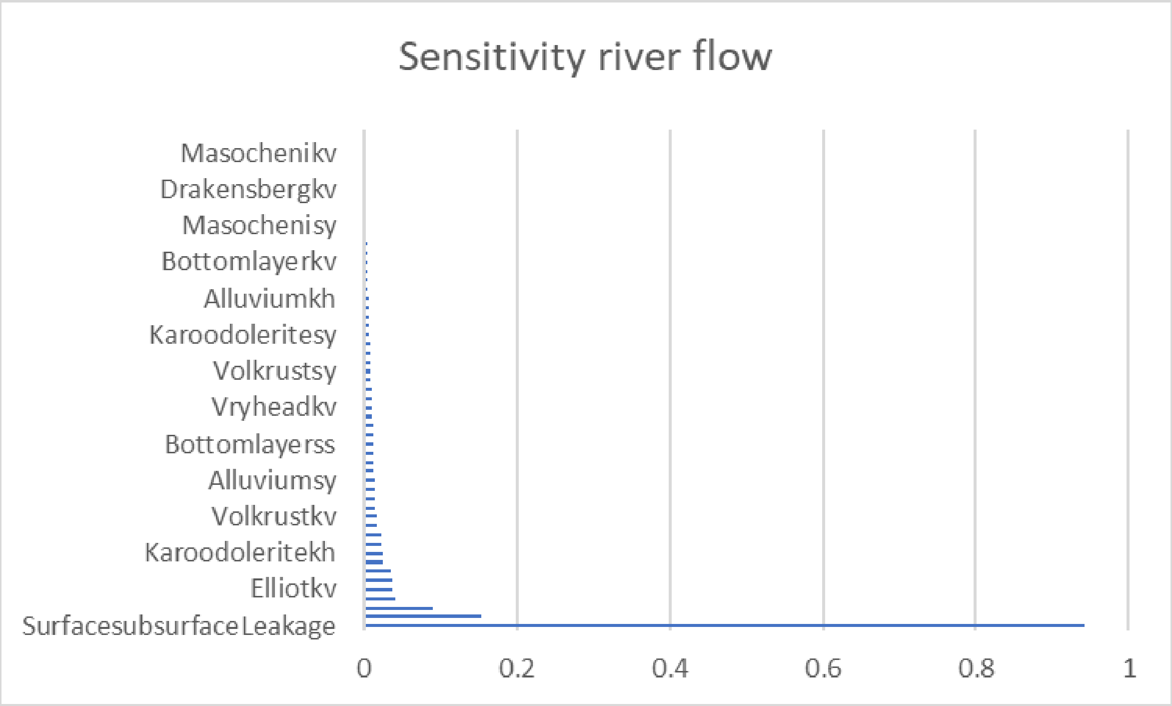
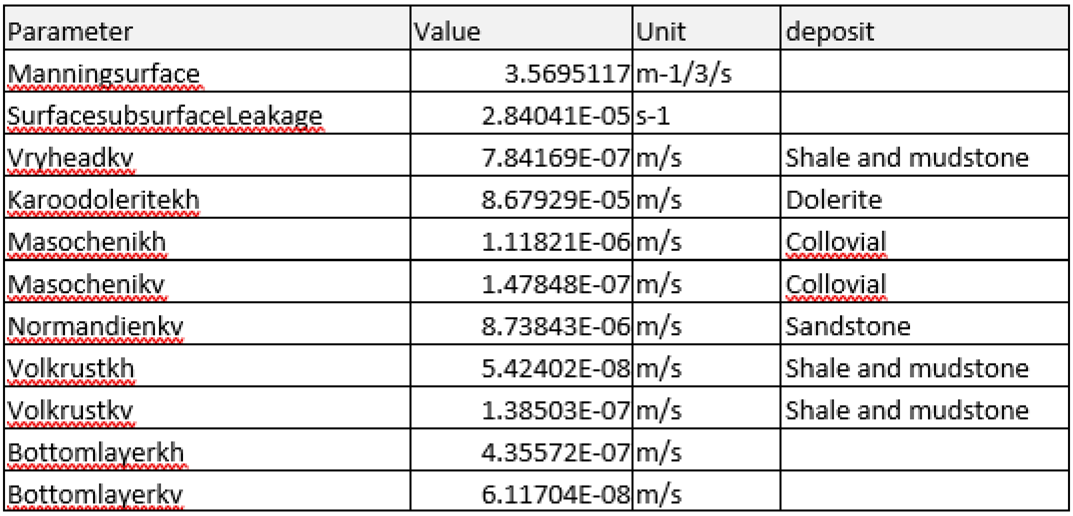


Figure 26 Sensitivity river flow – regional model

5.8 Regional model results

5.8.1 Groundwater

For the automatic calibration of the regional model the weight was laid on the most sensitive parameters shown on Figure 25 and Figure 26 including sensitive parameters for both groundwater and river flow. Parameters with a sensitivity more than 5 % of the most sensitive parameter has been selected and are shown in Table 3 together with the optimized values.



Parameter	Value	Unit	deposit
Manningsurface	3.5695117	m-1/3/s	
SurfacesubsurfaceLeakage	2.84041E-05	s-1	
Vryheadkv	7.84169E-07	m/s	Shale and mudstone
Karoodoleritekh	8.67929E-05	m/s	Dolerite
Masochenikh	1.11821E-06	m/s	Collovial
Masochenikv	1.47848E-07	m/s	Collovial
Normandienkv	8.73843E-06	m/s	Sandstone
Volkrustkh	5.42402E-08	m/s	Shale and mudstone
Volkrustkv	1.38503E-07	m/s	Shale and mudstone
Bottomlayerkh	4.35572E-07	m/s	
Bottomlayerkv	6.11704E-08	m/s	

Table 3 Sensitive parameters

The optimized hydraulic conductivities agree within the limits for what you expect for the corresponding deposits. The optimized hydraulic conductivity is highest for sandstone and dolerite and lowest for shale and mudstone.

After woods the hydraulic conductivities were tested against all groundwater targets within the area. The mean errors between observed and simulated heads, Figure 27, are generally large, also compared to results commonly obtained in Denmark. The large variations in the model errors with neighboring wells showing more than +10m and -10m error respectively, indicates a very complex hydrogeology, not captured by the simplified geological model. The large topographical variation further adds to the errors, as this variation is only partially resolved by the relative coarse model grid. It is therefore evaluated that a significate improvement in the model fit can only be obtained by improving the geological model. The purpose of the regional model has been to define flow boundaries to the local model. As can be seen, the model performance change along the border, both overestimating and underestimating the groundwater heads. Hence, the errors in the model performance does not results in a biased boundary condition for the smaller scale models.

The simulated potential head maps in layer 2 is shown in Figure 28, the highest simulated heads is in the upstream end at Drakensberg Mountains, where the simulated heads is above 3000 meters above sea level. In the most downstream part, where Thukela River flows out of the area, the simulated potential head is lowest and around 500 meters above sea level.

An example of simulated heads versus observed heads is shown in Figure 29. In general, the regional model simulates a smaller annual fluctuation of the water table than observed, probably because the fluctuations are very much dependent on local recharge through faults and dykes which is not described in the model.

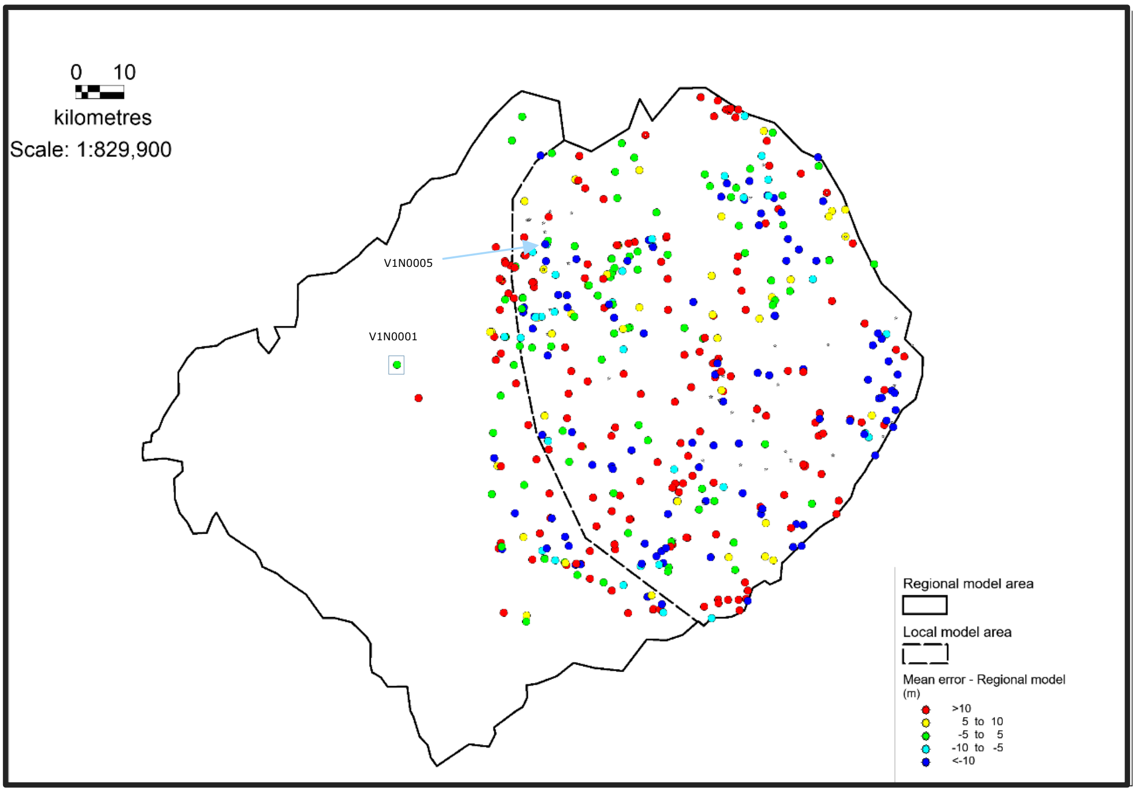


Figure 27 Results from the calibration of the regional model with respect to groundwater heads. Mean error is the average difference between simulated and observed heads

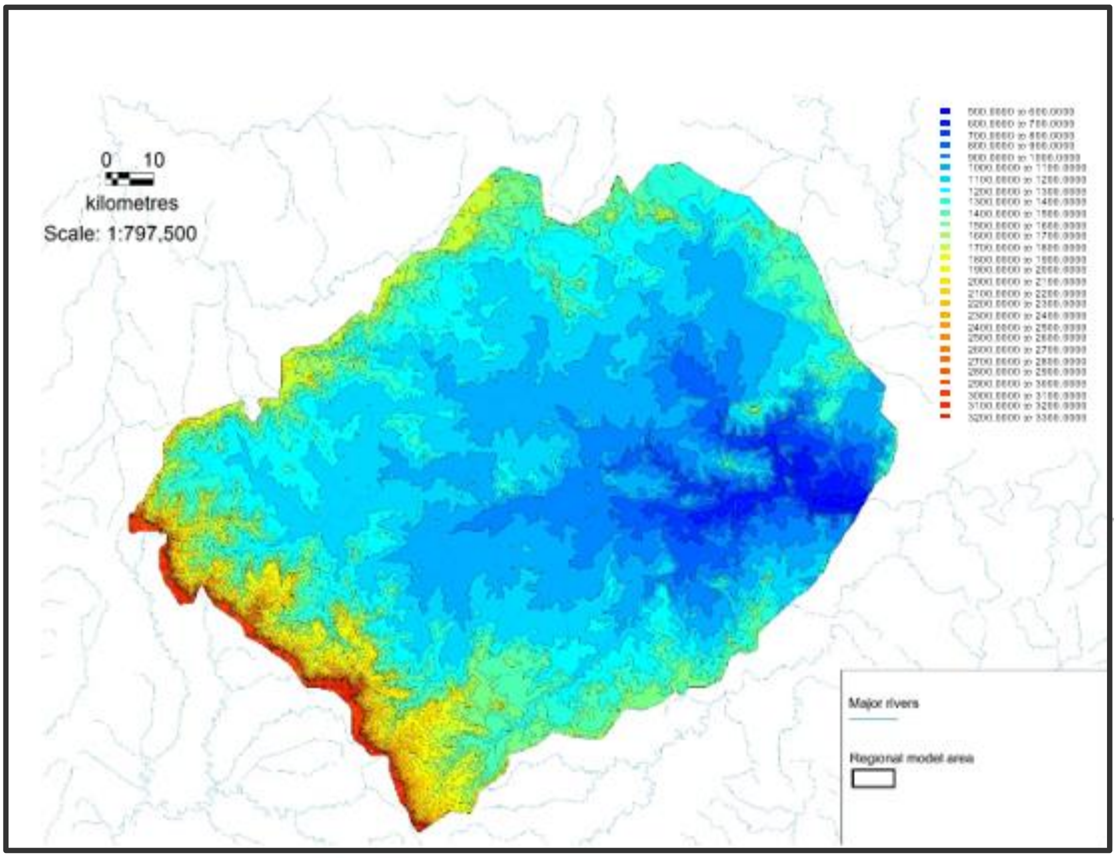


Figure 28 Simulated potential head map in layer 2 in the regional model. Values are in meters above sea level.

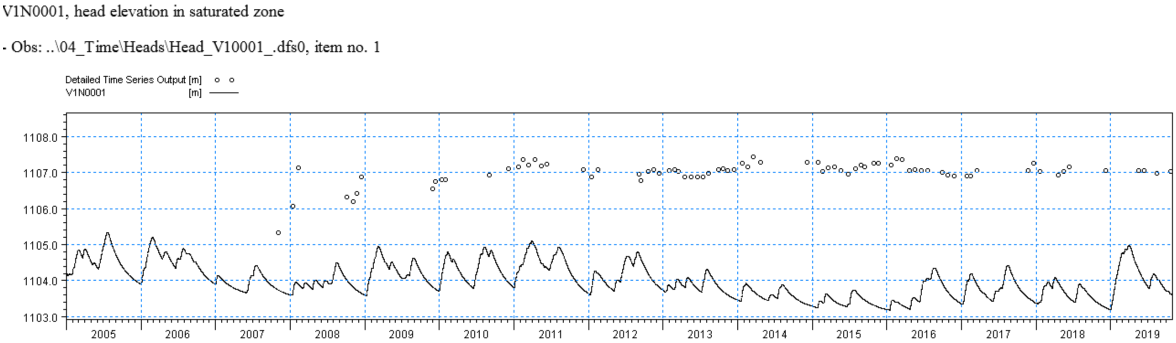


Figure 29 Simulated versus observed heads in well no. V1N0001. The location is shown on Figure 27.

5.9 Rivers

In many rivers a discharge variation as shown on Figure 30 is simulated, with the highest discharge in the wet season in the first months of the year, and decreasing discharge in the dry season from September to December.

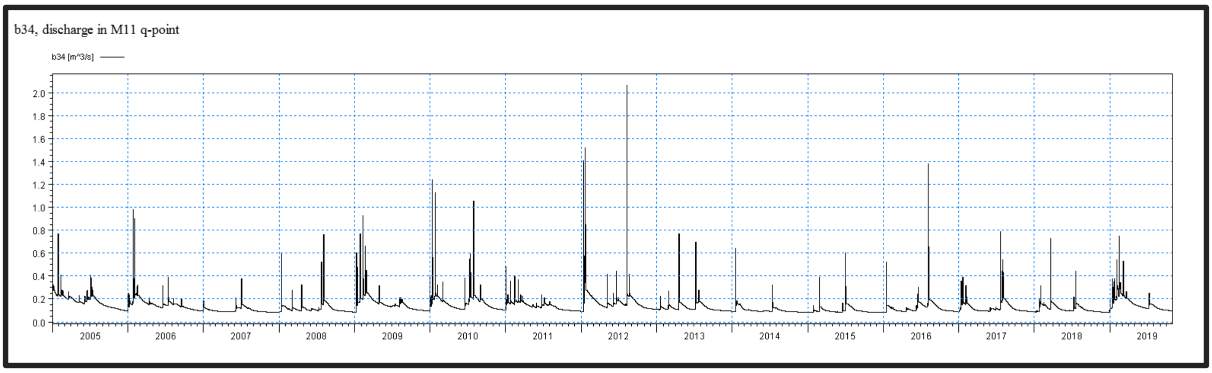


Figure 30 Simulated river discharge in Boesmans River

Error! Reference source not found. shows the measured river discharge from the stations shown in Figure 24. The largest discharge is measured at station V1H001, which is in the Tugela River, the main river in the area with the largest catchment originating in The Drakensberg Mountains. In the tributaries the measured river discharge is smaller.

It can be seen in **Error! Reference source not found.** that the river discharge is generally lower after 2011 indicating more dry conditions in this period. The observed versus simulated discharges are shown in Figure 31 to Figure 34, where the mean error (ME) is also included . The model generally simulates a lower discharge than observed (positive ME). There are probably several reasons for this: one important reason is probably that the amount of rain is larger in the mountainous area due to the increased elevation, which is not implemented in the model. Another reason is the simplified river cross sections and limited information about the contact between the river and fractures.

In the river of Tugela, the model is not able to simulate the high discharge observed in the wet season and high rain events.

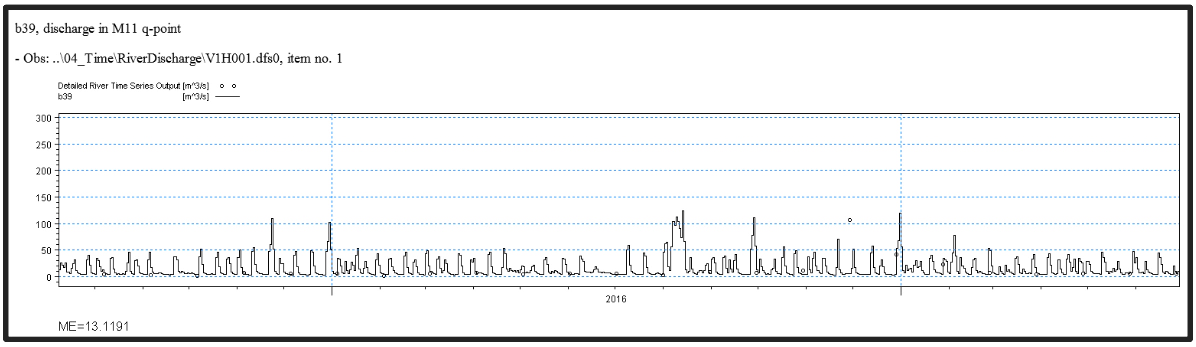


Figure 31 Simulated versus measured heads at station V1H001 in Tugela River

In the Sunday River, the model simulates the observed discharge with greater accuracy in the upstream parts, as can be seen from Figure 32, but loses water in the river further downstream.

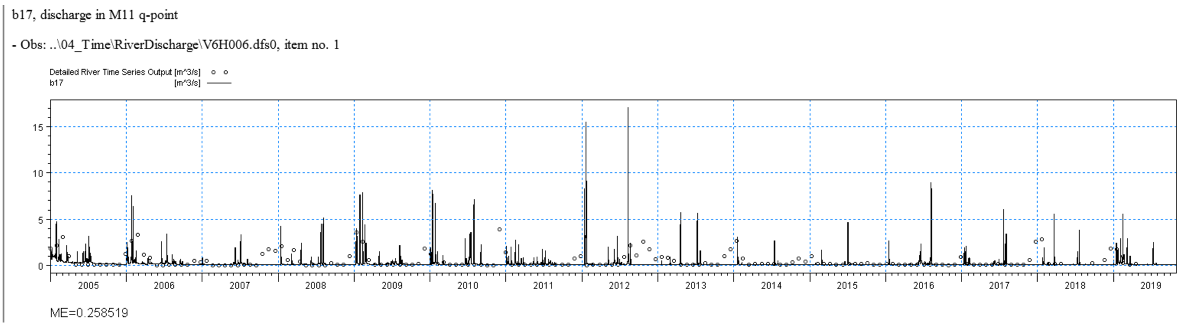


Figure 32 Simulated versus measured heads at station V1H006 in Sunday River, upstream

In the Wasbank River there is a better agreement between observed and simulated discharge, but the model has a tendency to simulate a too steep hydrograph, and do not simulate the "tail" (falling limb) which follows a rain event and seen in the observed values. The failure in describing the falling limb on the hydrograph is seen in other river stretches. This could indicate that the regional model simulates a too little groundwater recharge in these areas, because the direct runoff (resulting in high peaks) is too large compared to the subsurface flow.

In other areas, like in the Klip River, the model simulates too low river discharges similar to the lower part of Sunday river, which could indicate that the subsurface flow is overestimated in this area.

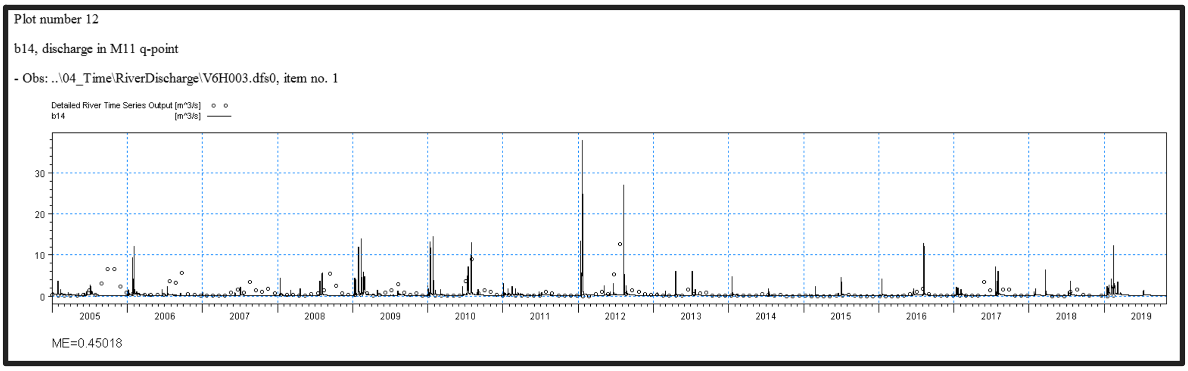


Figure 33 Simulated versus measured heads at station V1H003 in Wasbank River

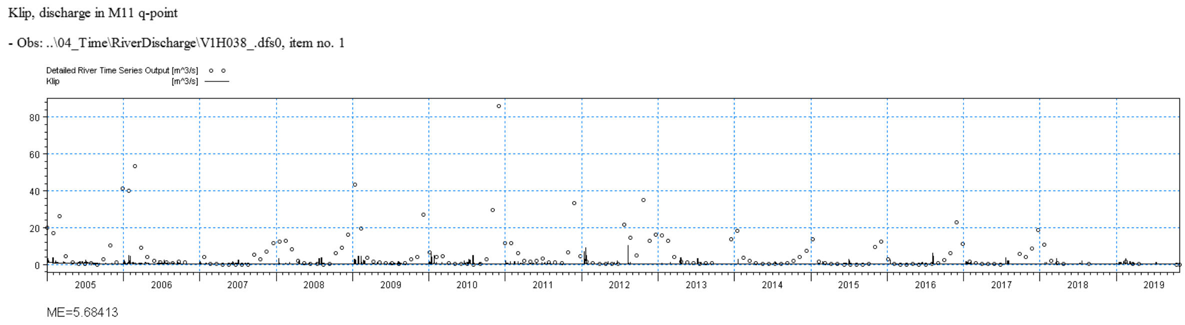


Figure 34 Simulated versus measured heads at station V1H038 in Klip River

The model performance with regards to simulating river discharge is in general not very accurate. One of the reasons for this could be that the operations of the upstream dams is not included. Despite this, it has been found reasonable to use the simulated river discharge in the regional model as inflow in the local model. For future assessments it is recommended to upgrade the river system and include a detailed description of how the dams are operated. If this is done it will be possible to use the integrated model system to manage both surface water and groundwater as a combined system.

6. LOCAL MODEL

The locale model covers the target areas for Umgeni Water and has an area of 6424 km^2. It is in the downstream end of the regional model area. In the local model the highest elevated areas are around 1800 meters above sea level and lowest areas around 500 meters above sea level.

The grid size of the regional model is 250 meters. The simulation period is 2005-2019 with a time step of 24 hours in the saturated zone, the same as in the regional model.

6.1 Hydrostratigraphical model

The hydro stratigraphical model is based on the voxel model as shown on Figure 35, with a discretization of 250 x 250 meters in the horizontal plane and 10 meters in the vertical plane. In the voxel model the geological units are distributed on shale, sandstone, and dolerite, so the distribution follows hydraulic properties and not geologic formations. Moreover, a layer is specified in the upper 10 meters below ground surface, with properties as a regolith that is a weathered zone characterized by a general low hydraulic conductivity but a high storage capacity.

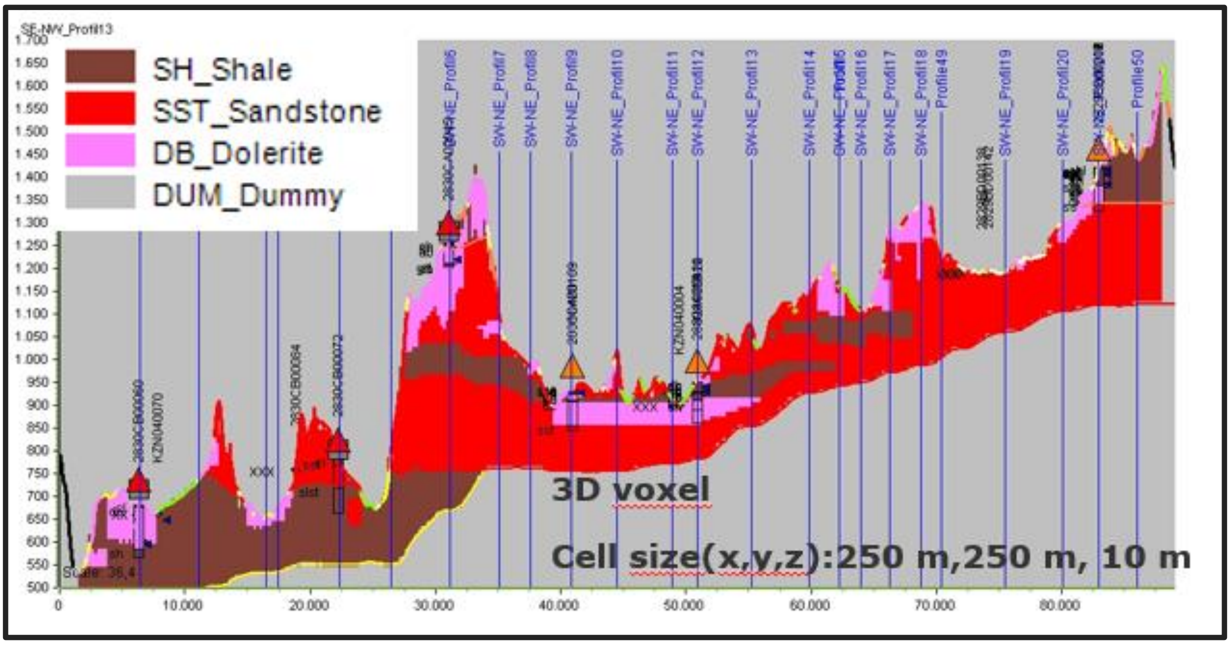


Figure 35 Cross-section of the voxel model

6.2 Implementation of faults and fractures

Faults and fractures have been implemented in the local model as lenses. It has not been possible to identify vertical fractures related to dykes but are included to the extent that they are covered by already identified faults. The faults are implemented in the model as vertical lenses and as a positive hydraulic boundary, which is a zone with a high hydraulic conductivity. This is a simplification, as the faults will have an inclination. Furthermore, some faults will probably act as a negative hydraulic boundary.

Moreover, a system of 6 horizontal fractures has been implemented as lenses in the model at respectively 15, 25, 37, 62, 103 and 140 meters below ground surface (indicated on Figure 38).

Horizontal fractures can be found in other depths as well, but the depths implemented were identified as the most common. The depths have been identified by an analysis of depth to water strikes in boreholes from NGO and Umgeni water. The frequency of the depth to the water strikes are shown in Figure 36, and as can be seen the highest frequency is within the upper 50 meters below ground surface. The horizontal fractures have been distributed in the entire local model area and each horizontal fracture layer is separated from each other by a non-fractured layer.

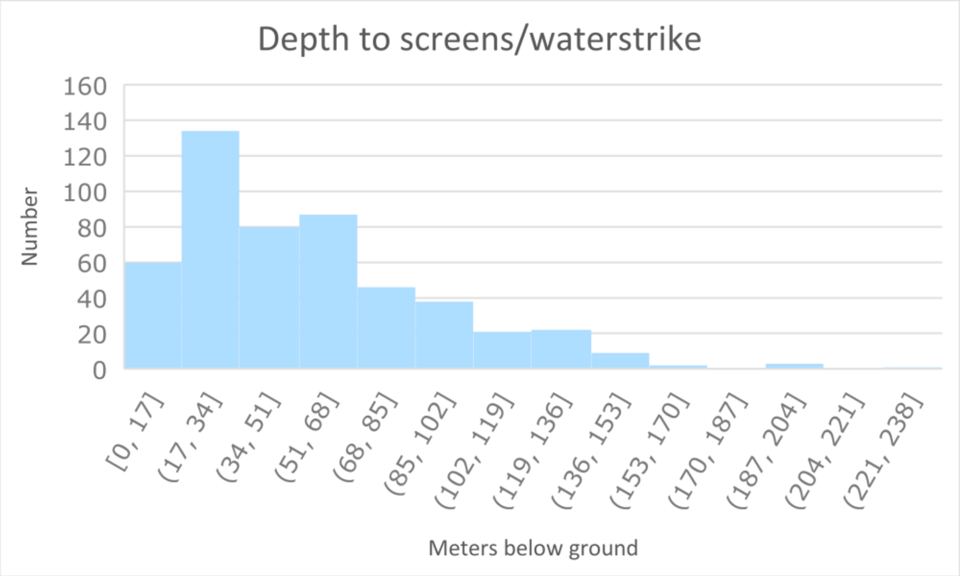


Figure 36 Histogram over Depth to water strikes

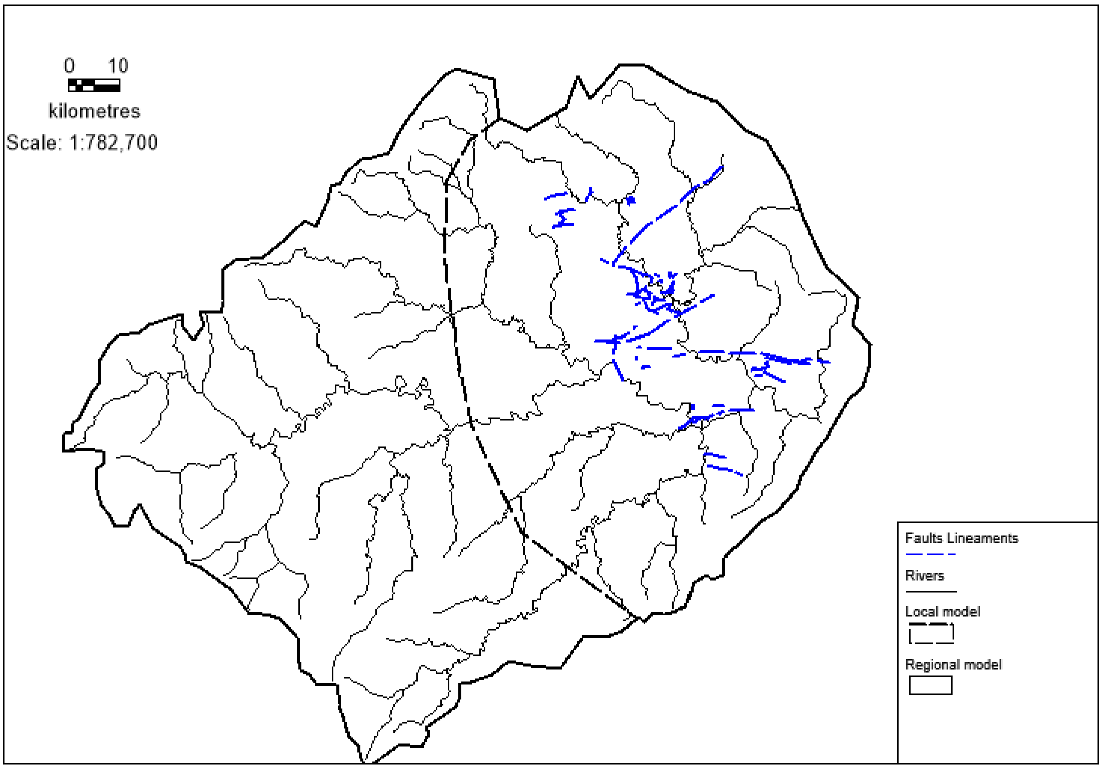


Figure 37 Previous identified faults lineament

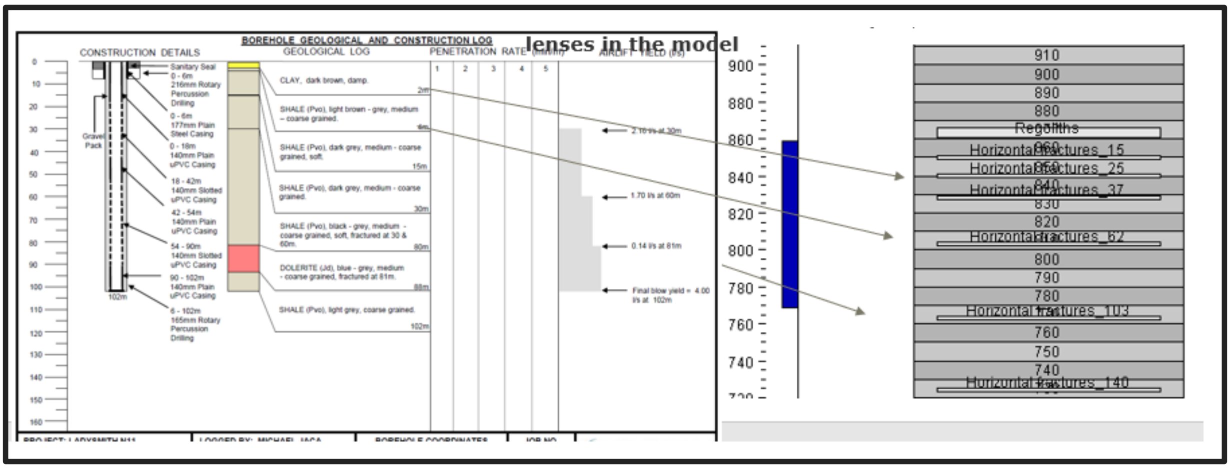


Figure 38 Horizontal fractures

6.3 Rivers

The river setup from the regional model is used also for the local model, where the rivers have been cut off near the boundary between the local and regional model. In these calculation points dynamic river flows has been implemented from the regional model.

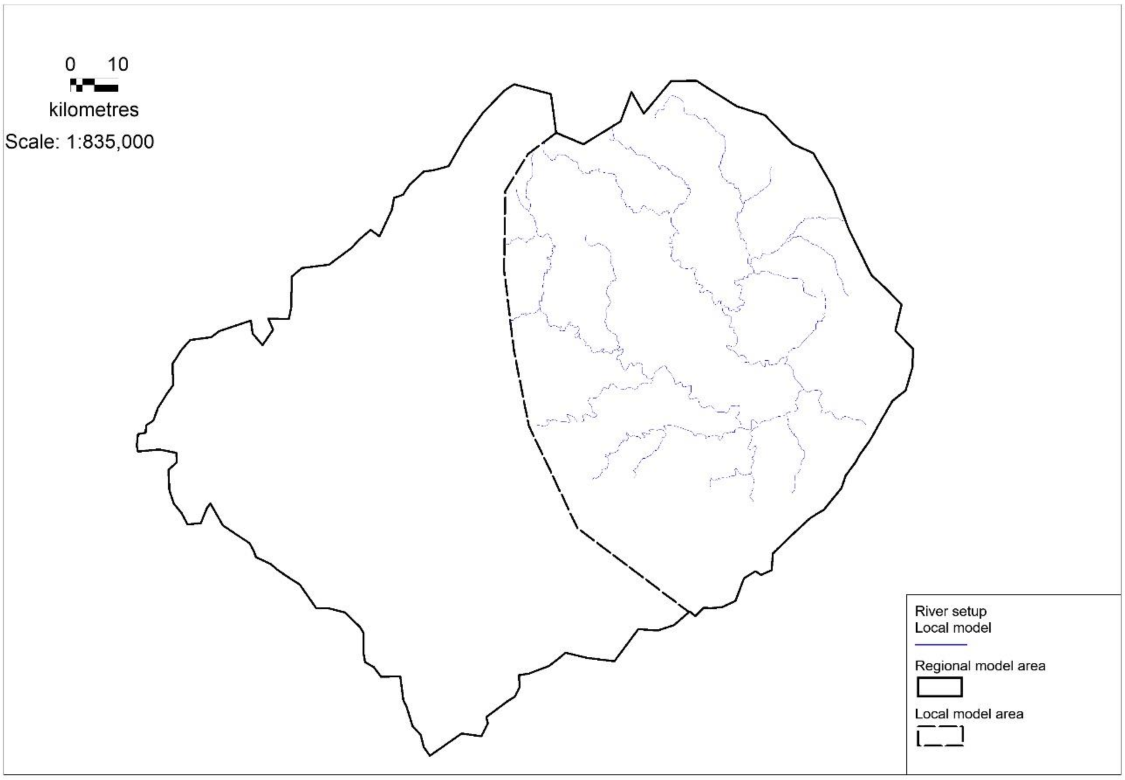


Figure 39 Rivers in the local model

6.4 Calibration methodology

The best calibration methodology was discussed before the calibration was started. It was concluded that the best strategy would be to calibrate on a well-defined smaller area with good calibration data in time and space from specific geological units and then extrapolate the calibrated parameters to the rest of the area (like the former Danish GRUMO-areas which were monitored very detailed). However, it was difficult to find an area with well-defined boundary conditions, and the calibration was based on the whole area and included older and more uncertain data.

The model was calibrated on the period 2012-2016 with a warm-up period on 5 years, and there was only optimized on groundwater heads. The groundwater targets used in the calibration is shown on Figure 42. A total of 168 monitoring wells were selected for the calibration of the model including Umgeni Water´s monitoring boreholes (some were also used for validation), the groundwater sites with time series and selected NGA boreholes. With regards to NGA boreholes both older data from the period 1950-2000 has also been selected to get a good coverage of the model area. Older groundwater head observations have been implemented at the date of 1st of January 2015, which is just at the end of the dry season, so they are assumed to represent a low water table. Besides to give a good coverage of the area the selected targets har also been selected to give a good representation of the geological units. About 50 % of the screens were related to dolerite and 25 % each for sandstone and shale respectively as can be seen on Figure 40.

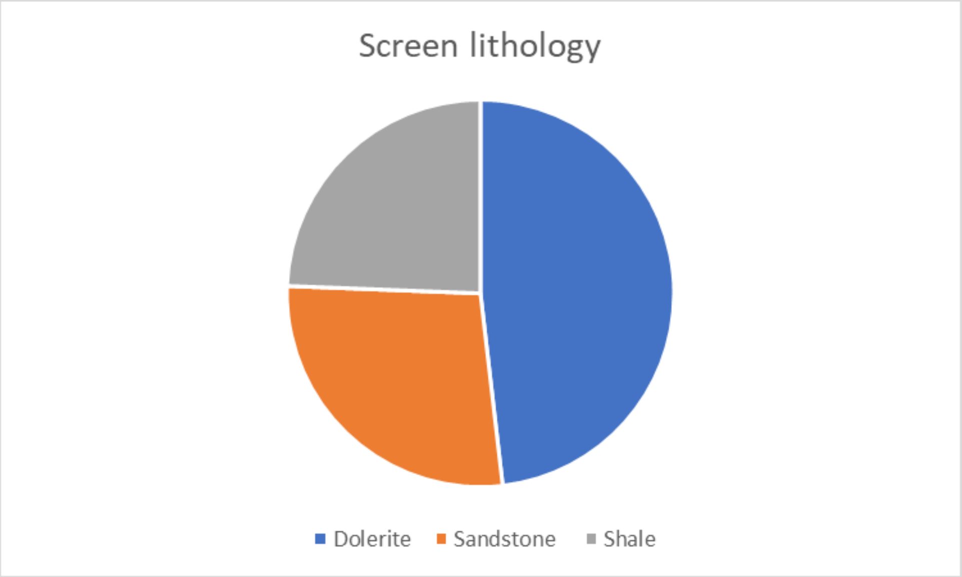


Figure 40 Screen lithologi

6.5 Sensitivity analysis – local model

The result from the sensitivity analysis is shown in Table 4. The result shows that the most sensitive parameter is the vertical hydraulic conductivity in the shale unit followed by hydraulic parameters in the regolith and fractures. The green parameters were selected for the calibration of the local model. Moreover, the blue parameters were selected as additional parameters for calibration, even though they didn't turn out to be highly sensitive. They were also chosen because they were expected to be sensitive and because the sensitivity can change during the calibration.

Parameter	Sensitivity
Shale_kz	18.302
Regolith_kz	18.289
Horisontal_Fractures_kx	17.938
Sandstone_kx	2.432
Shale_kx	1.466
Shale_ss	1.357
Horisontal_Fractures_kz	0.92
Shale_Sy	0.706
Sandstone_kz	0.368
Sandstone_Sy	0.33
Sandstone_SS	0.327

Dolerit_kz	0.165
Dolerite_Sy	0.072
Horisontal_Fractures_sy	0.06
Dolerite_SS	0.04
Dolerit_kx	0.032
VerticaleFractures_kx	0.012
Horisontal_Fractures_ss	0.012
Regolith_kx	0.011
Regolith_ss	0.011
VerticaleFractures_ss	0.009
VerticaleFractures_kz	0.005
Regolith_sy	0.001
VerticaleFractures_sy	0.003

Table 4 Results from the sensitivity analysis

6.6 Calibration and validation

The chosen calibration strategy has not been a normal split-sample test, because it was difficult to get a satisfying groundwater head measurements coverage of the model area in two different time periods. Instead, the model was tested (or validated) on a smaller area which were not a part of the calibration process (proxy-basin test). This model area (named validation area in Figure 42) have a gridsize on 67.5 meters and with boundary inflow determined from the regional model.

The automatic calibration converged after 109 model runs and the optimized parameters are shown in Table 5. The optimized parameters are assessed to be within realistic range for the specific lithology. With regards to shale, sandstone and dolerite, shale has the lowest estimated hydraulic conductivity and dolerite the highest. The highest hydraulic conductivities are estimated in fractures and the highest specific yield are estimated in the regolith's. Only thing to highlight is that the vertical hydraulic conductivity in the shale is higher than the horizontal (maybe because the model is missing some vertical fractures).

Lithology	kx (m/s)	Kz (m/s)	Specific yield	Specific storage
Shale	5.01E-08	8.39E-08	0.05	3.89E-05
Sandstone	9.43E-07	1.07E-07	0.1	0.0001
Dolerite	8.75E-05	1.68E-05	0.05	0.0001
Air	0.0001	1.00E-05	0.1	0.0001
Verticale Faults	1.00E-05	1.34E-05	0.05	0.0001
Regolith	1.00E-06	4.77E-07	0.387717	0.0001
Horizontal fractures	0.000353272	1.21E-07	0.05	0.0001
Dykes	1.00E-05	0.001	0.05	0.0001

Table 5 Hydraulic parameters in the model. The calibrated parameters are marked by green

Based on the optimized values in Table 5 the model performance was evaluated.

According do Danish standard in hydrological modelling, a model's suitability can be categories from a "Screening model", suitable for screening purposes only, to a "Detail model" for detailed studies with an intermediary "Conservative model" category. These categories are determined from the model performance, where two commonly used accuracy criteria (Criterion 1 and 4) is shown on Table 6 and Table 7. These two criteria are based on the relation between the model errors and the difference between highest and lowest measured groundwater head in the area, dHmax. The highest performance is the "Detail model". Even though the mean error is high in many boreholes and in average above 10 meters, the calibrated model falls within a detail model category, because dHmax is very high. For the validation area, criterion 1 similarly falls within a detail model category, while it is a conservative model based on criterion 2. But this is still assessed to be good, and support that the optimized hydraulic parameters is valid for the area in general.

		Calibration results	Screening model	Conservative model	detail model
Criterion 1	ME/dHmax	0.00243	0.05	0.025	0.01
Criterion 4	RMS/dHmax	0.02193	0.1	0.05	0.025

Figure 41 Performance criteria for local model – calibration. dHmax (difference between highest and lowest measured potential head) is 1000 meters. Total 184 targets

		Validation results	Screening model	Conservative model	detail model
Criterion 1	ME/dHmax	0.000425	0.05	0.025	0.01
Criterion 4	RMS/dHmax	0.0223	0.1	0.05	0.025

Table 6 Performance criteria for local model – validation against all groundwater targes within local model area not used in calibration. dHmax (difference between highest and lowest measured potential head) is 1000 meters. Total 384 targets

		Validation results	Screening model	Conservative model	detail model
Criterion 1	ME/dHmax	0.006	0.05	0.025	0.01
Criterion 4	RMS/dHmax	0.029	0.1	0.05	0.025

Table 7 Performance criteria for local model – validation against groundwater targes within small validation model area. dHmax (difference between highest and lowest measured potential head) is 350 meters. Total 88 targets

Another issue with regards to the model performance, is that the uncertainty on the measured heads are high. A third criterion in the Danish standard (Criterion 2) uses the standard deviation on the observations according to Table 8 as an expression for the uncertainty related to the observation. For a detail model, criterion 2 shall be less than 1.65. The challenge is to estimate the uncertainty in a highly fractured mountainous area. The contributions to the uncertainty are measure error, interpolation (from point to grid), heterogeneity, non-stationarity, and other effects. It is assessed that the uncertainty is especially high because of the geological heterogeneity and topographical variations. The dynamic model accounts for the seasonal variation in the climate, however, a lot of older data has been used, introducing an uncertainty related to the climatic variations from dry and wet years as well as annual variations. These uncertainties have been addressed by the non-stationarity term. With the uncertainty estimations in Table 8, the value of criterion 2 correspond to a value just at the border of a conservative model and a screening model for the local model, so the performance of the model changes with the criterion used.

	Measure error	Cote	Interpolation	Heterogenity	Non stationarity	Other effects	Sobs
Criterion 2	1	2	4	4	3	1	6.9

Table 8 Criterion 2 according to danish model guidelines

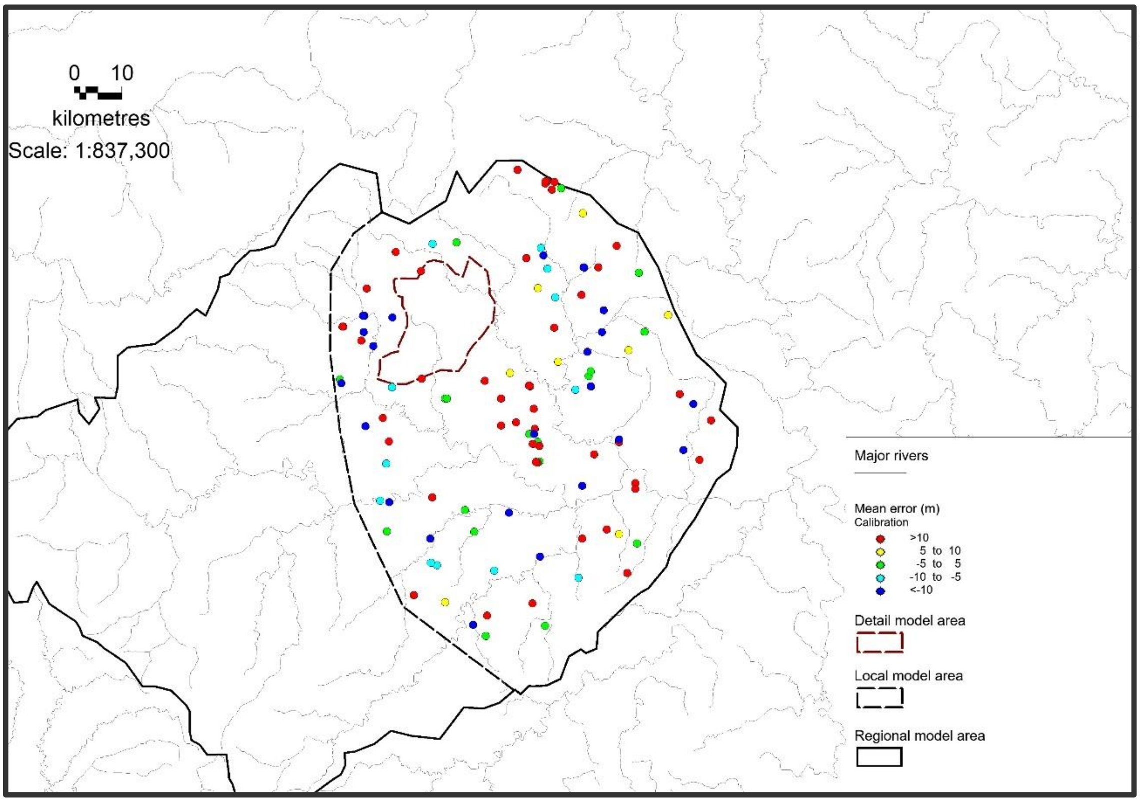


Figure 42 Mean error for groundwater targets used for the automatic calibration of the local model

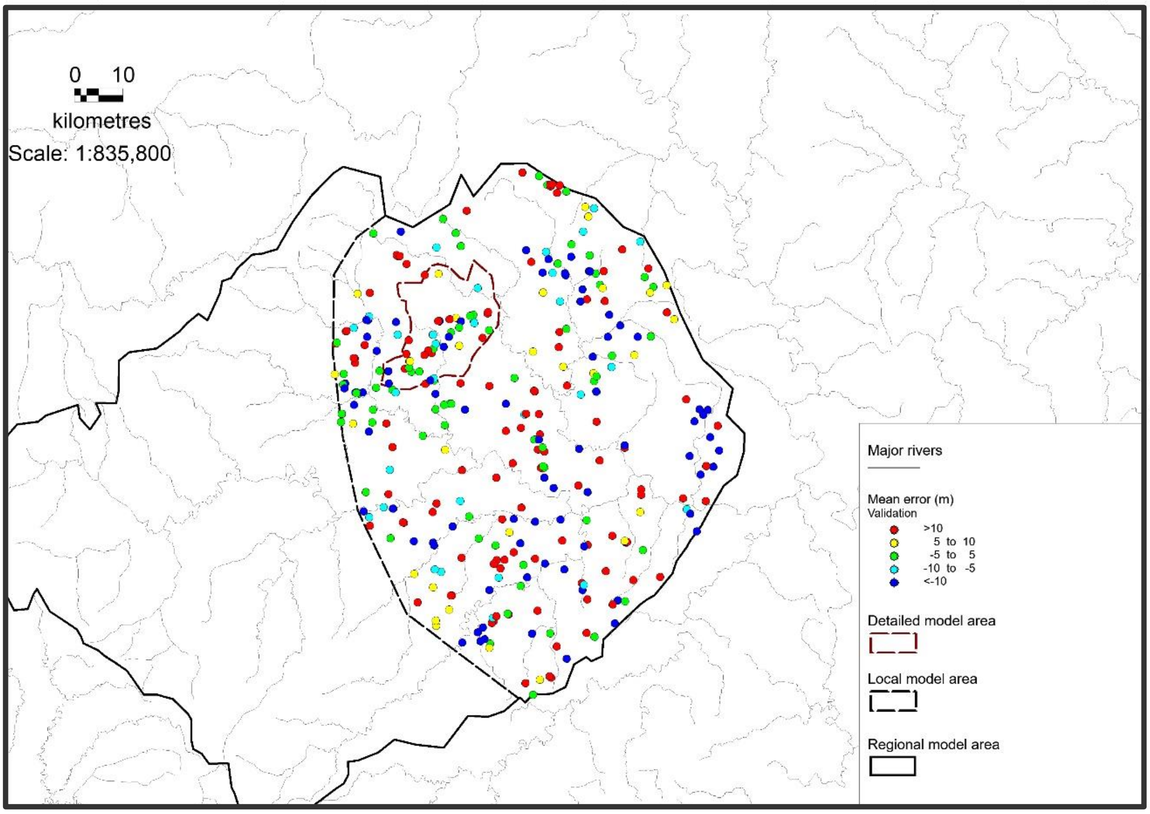


Figure 43 Distribution of Mean error for all groundwater targets within the local model area

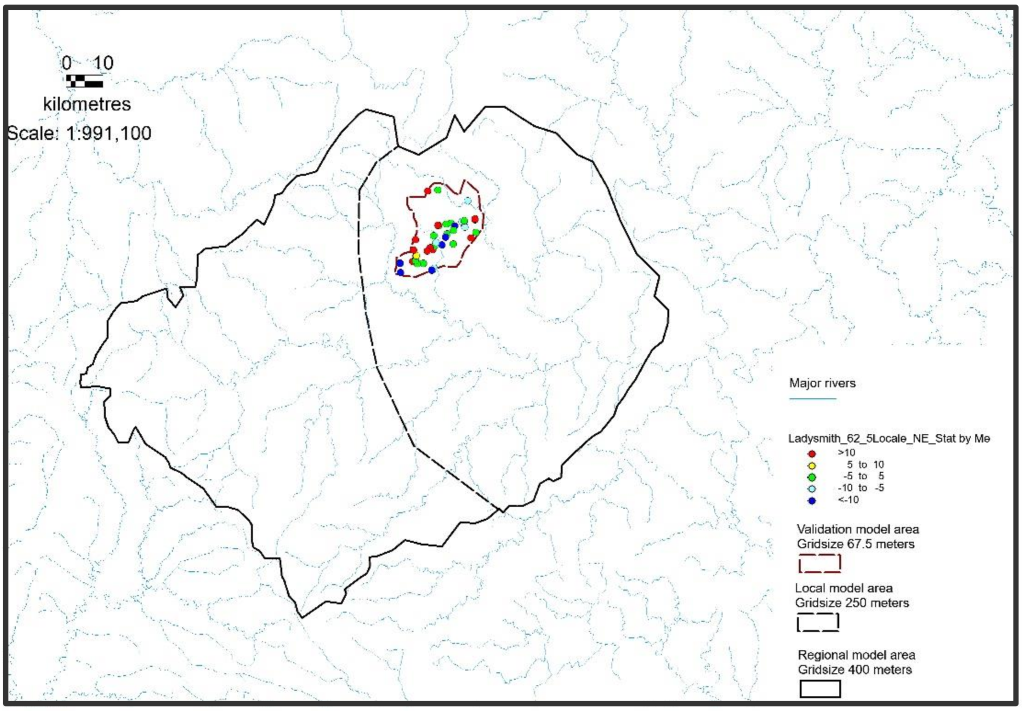


Figure 44 Mean error for groundwater targets used for the validation of the local model

With regards to the simulation of the variations in the groundwater levels, the observed annual variations in the groundwater head is 0.5-2 meters, while the simulated variation is within the same range as can be seen on Figure 45, Figure 47 and Figure 46. An example of a simulated water table in a shallow borehole is shown in Figure 46, it appears that in this example the simulated water table rises very quickly in the beginning of the wet season. In the deeper boreholes the impact on the groundwater table due to variations in the climate is generally more delayed. It appears also from the figures that during the simulation period there is a generally decrease in the water table due to the drier conditions at the end of the period.

Because high rates of recharge are expected to take place around dykes, the implementation of these in the model is important to simulate the observed variation in the groundwater table. Otherwise, the model will average the groundwater recharge which has the consequence that variations will be more blurred.

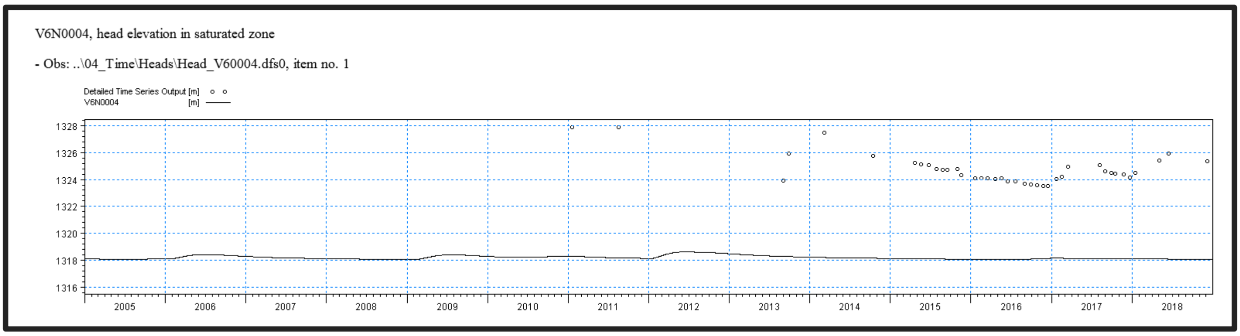


Figure 45 Simulated versus observed values in borehole nr. V60004

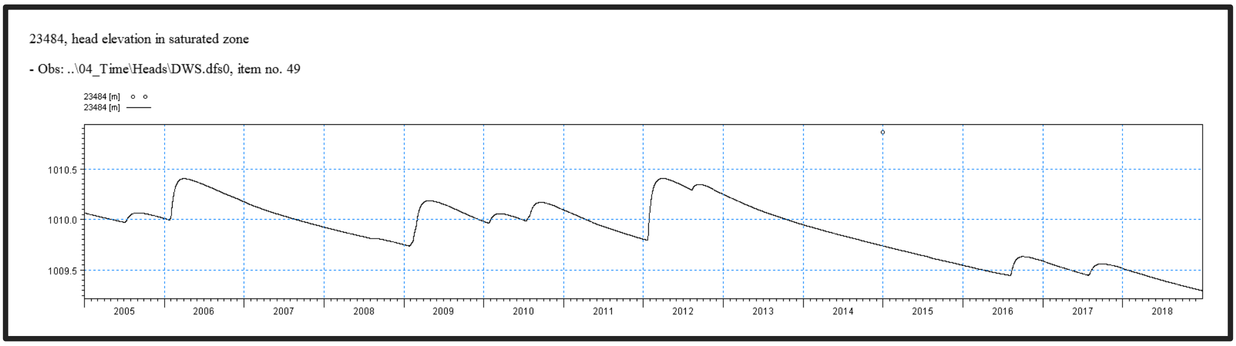


Figure 46 Simulated values in a shallow borehole (23 meters below ground surface)

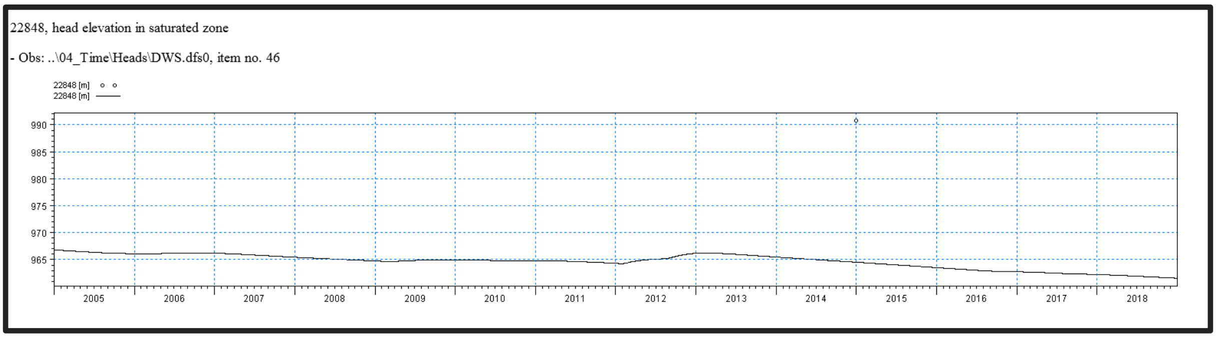


Figure 47 Simulated values in a deep borehole (75 meters below ground surface)

The performance of the river flow is only at screenings level and requires additional investigations, particularly a cross section survey in target rivers before improvement can be expected as well as a research on local drainage and more detailed hydrographs analyses to determine how much water is coming to the river as surface runoff or groundwater. Moreover, in the local model the rives has not been calibrated but only implemented for tests. An example from station V1H001 in Tugela River is seen on Figure 48 and from Wasbank River on Figure 49, where it appears that the local model has difficulties with simulating both high and low flows.

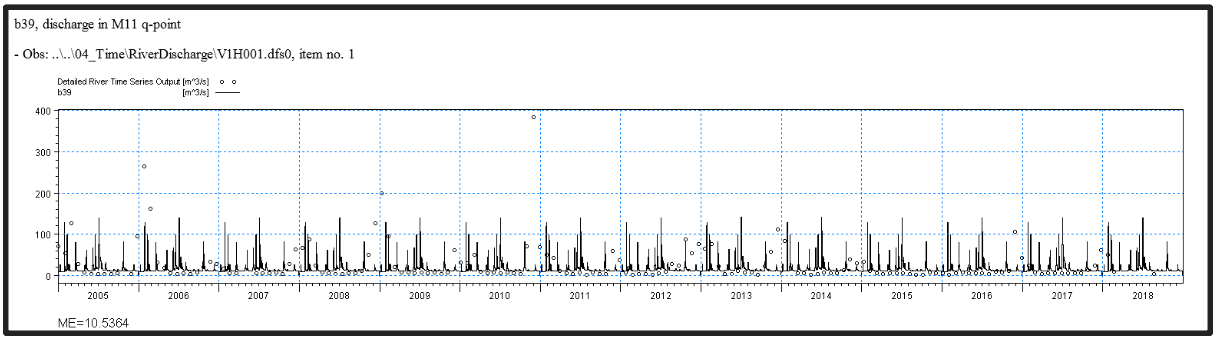


Figure 48 Simulated versus measured heads at station V1H001 in Tugela River

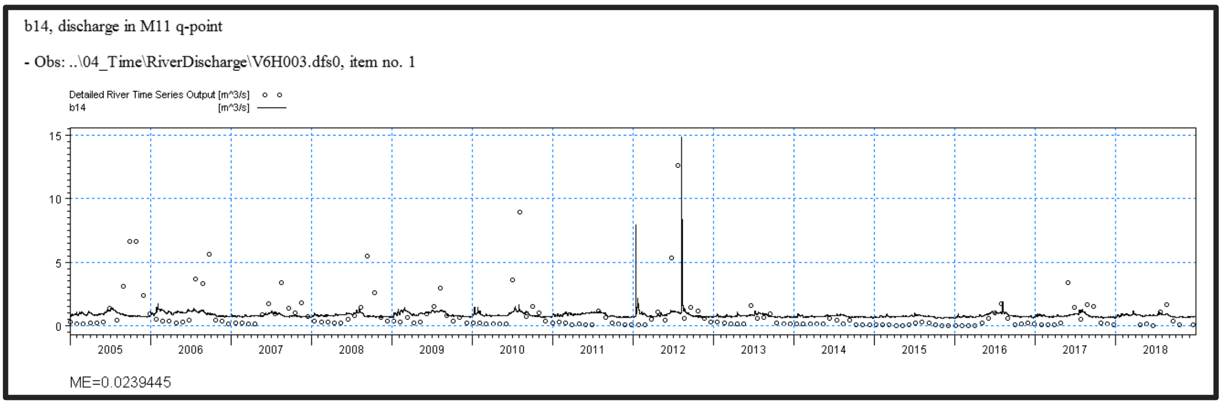


Figure 49 Simulated versus measured heads at station V1H003 in Wasbank River

7. SCENARIOS

Based on the local model three scenarios has been evaluated as shown in Table 9. Based on the baseline scenario – Scenario 1, transmissivities, groundwater recharge and potential head maps has been extracted from the model simulations and shown on maps. The transmissivity maps have been used to identify potential well sites, which have been further tested in two well field scenarios – scenario 2 and scenario 3.

		Groundwater recharge	Sustainable abstraction rates	Potential head maps	Discharge zones	Drawdowns	Transmissivity map	Potential well sites	Catchment areas
Scenario 1	Scenario describing the current situation	x	x	x			x	x	
Scenario 2	Modelling new target area for Umgeni Water before new wells are developed	x	x	x	x	x			x
Scenario 3	Modelling new target area for Umgeni Water before new wells are developed	x	x	x	x	x			x

Table 9 Description of scenarios

7.1 Scenario 1- baseline scenario

Scenario 1 is the baseline scenario describing the current situation. Current groundwater abstractions with a registered license in the Warm database /2/ are included in the baseline scenario.

Results from scenario 1 provide the basis for scenario 2 and 3. Figure 50 shows the transmissivity from zero to hundred meters below ground surface based on the detailed geological voxel model and calibrated hydraulic conductivities. The transmissivity variation is very high and boundaries sharp, reflecting the distribution of shale, dolerite, and sandstone. Areas with higher transmissivities are associated to the distribution of dolerite and sandstone. Comparing the transmissivity distribution with the results from the blow yield, there does not seem to be a straightforward relationship. Within the higher transmissivity areas, the blow yield values vary from low to higher yields without a significant pattern.

Figure 50 shows the transmissivity 100-200 meters below the ground surface. It appears that the transmissivity generally is lower than 0-100 meters below ground surface which indicate the best aquifers are in the upper 100 meters below ground surface. Based on the transmissivity distribution several potential wellfield areas can be identified as indicated in Figure 52. Within these areas the best locations can be selected based on elevation and location of current distribution grid.

In Figure 53 is the distribution of average annual groundwater recharge shown. As can be seen in the figure the simulated recharge to the groundwater is below 10 mm/year in large parts of the area. Higher groundwater recharge has especially been simulated along the borders of the mountains, where surface water/rainwater are flowing down the hilly slopes to lower areas, and infiltrates to the groundwater at the foothills of the mountains. Along the river’s groundwater discharge into the rivers, and the recharge is thus generally low in these areas. A combination of high groundwater recharge and high transmissivity has the highest potential for groundwater abstraction.

The vertical groundwater flow 30 meters below ground surface is shown in Figure 54. Compared to the recharge to the uppermost groundwater table, the areas with upward groundwater flow has increased. Moreover, it can be seen that at several of the identified faults lineaments, there is an increased simulated groundwater flow to the deeper aquifers which is also very beneficially for groundwater abstraction.

An example of simulated groundwater potential head in a geological layers 80 meters below ground surface is shown in Figure 55. The groundwater head variation is from approximately 500 meters to almost 1600 meters above sea level in the mountainous areas. Figure 56 shows the simulated average flow in the rivers in the model discharge calculation points (the southern calculation points is starting within the local model area due to some earlier adjustments of the southern border, but still with input from the regional models nearest calculation points). The simulated average discharge increases downstream, with the highest discharge in the main rives and smaller discharge in smaller tributaries. The change in simulated average discharge between calculation points, i.e. the discharge increase between an up- and downstream point, is shown in Figure 57. High changes indicated areas where the total inflow to the river is high (both surface water and groundwater), for examples taking place at some stretches at Tugela River. It should be noted though that the simulated river discharge is not very accurate, and only at screening level.

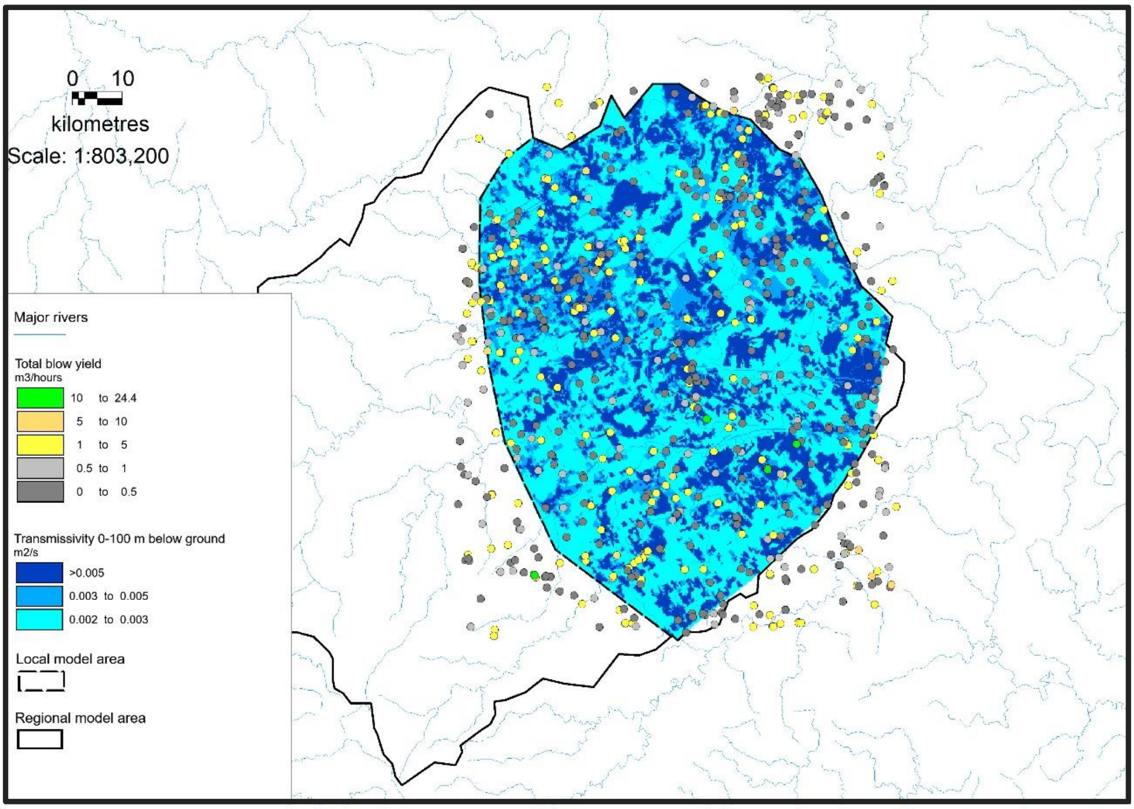


Figure 50 Transmissivity 0-100 meters below ground surface

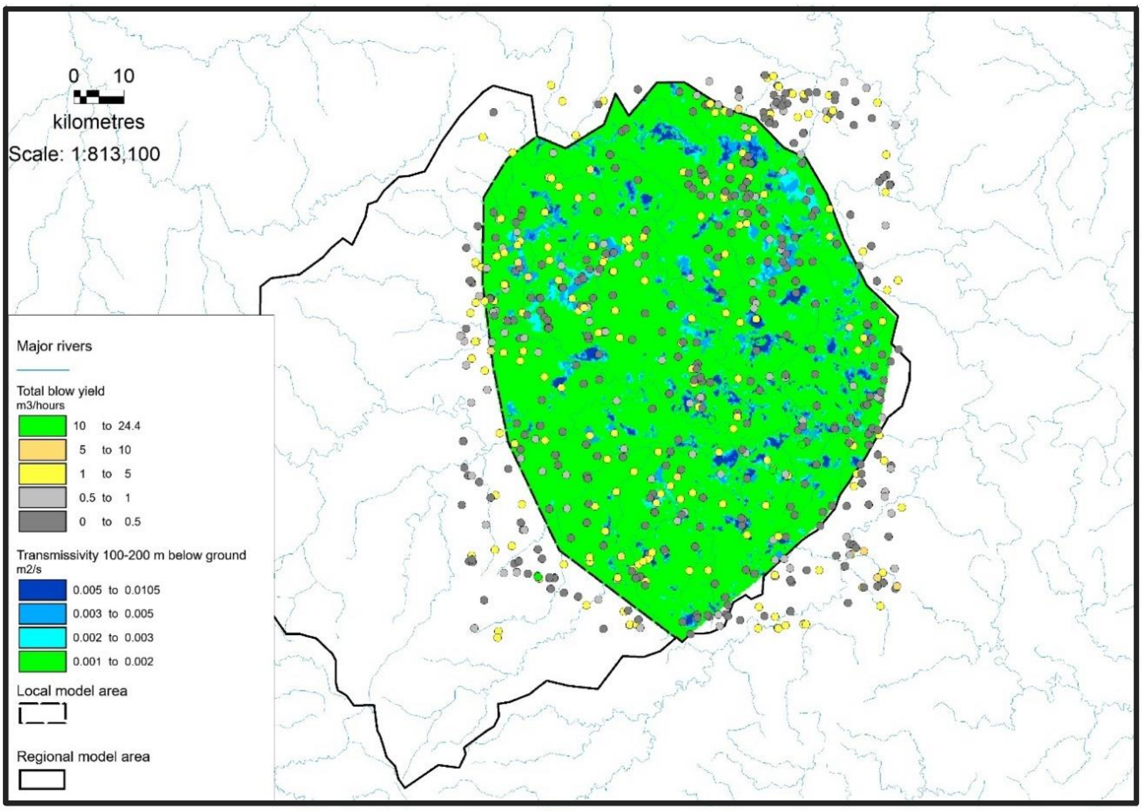


Figure 51 Transmissivity 100-200 meters below ground surface

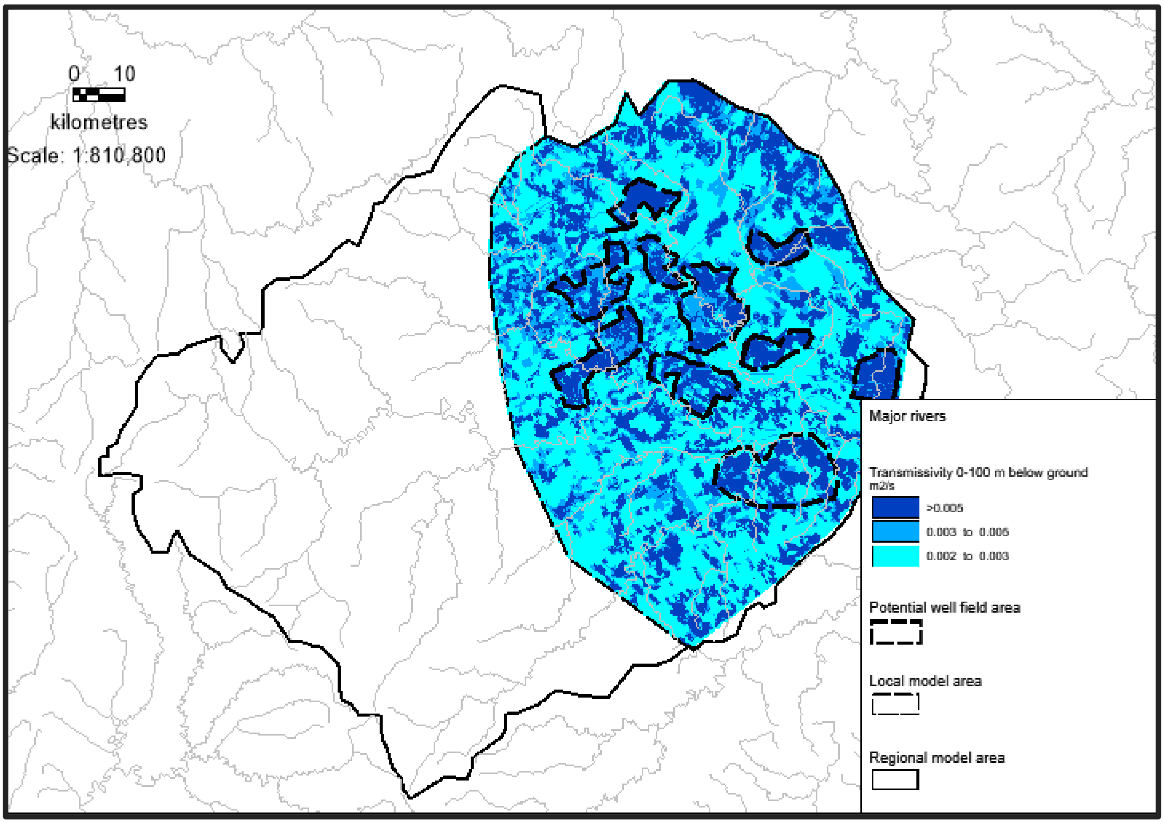


Figure 52 Potential well field areas

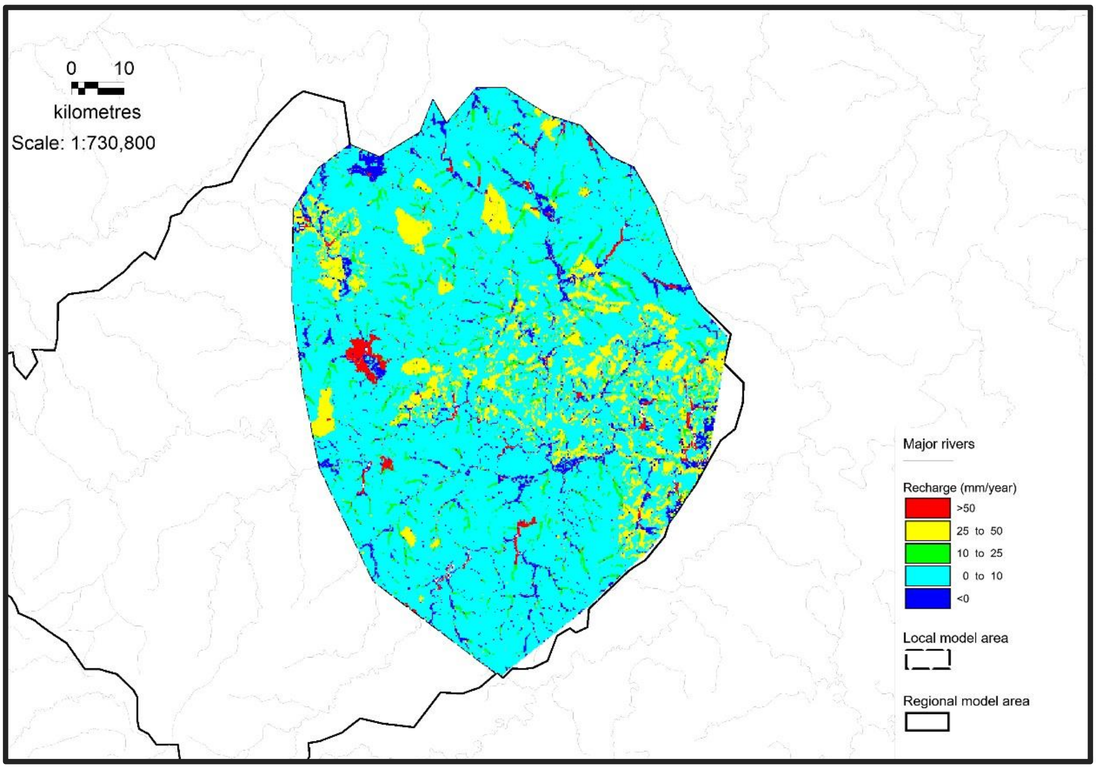


Figure 53 Distribution of the annual average recharge for the period 2008-2018. The simulated recharge is generally highest along the foothills of the mountains

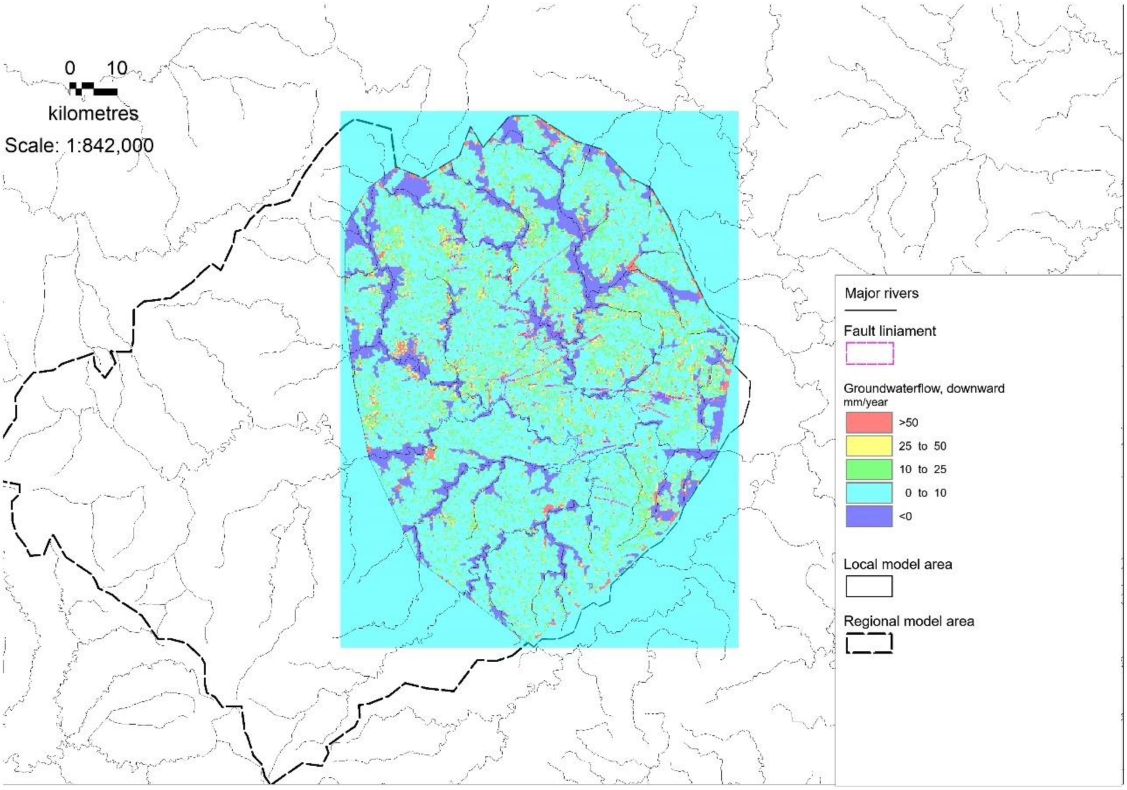


Figure 54 Vertical groundwater flow 30 meters below ground surface

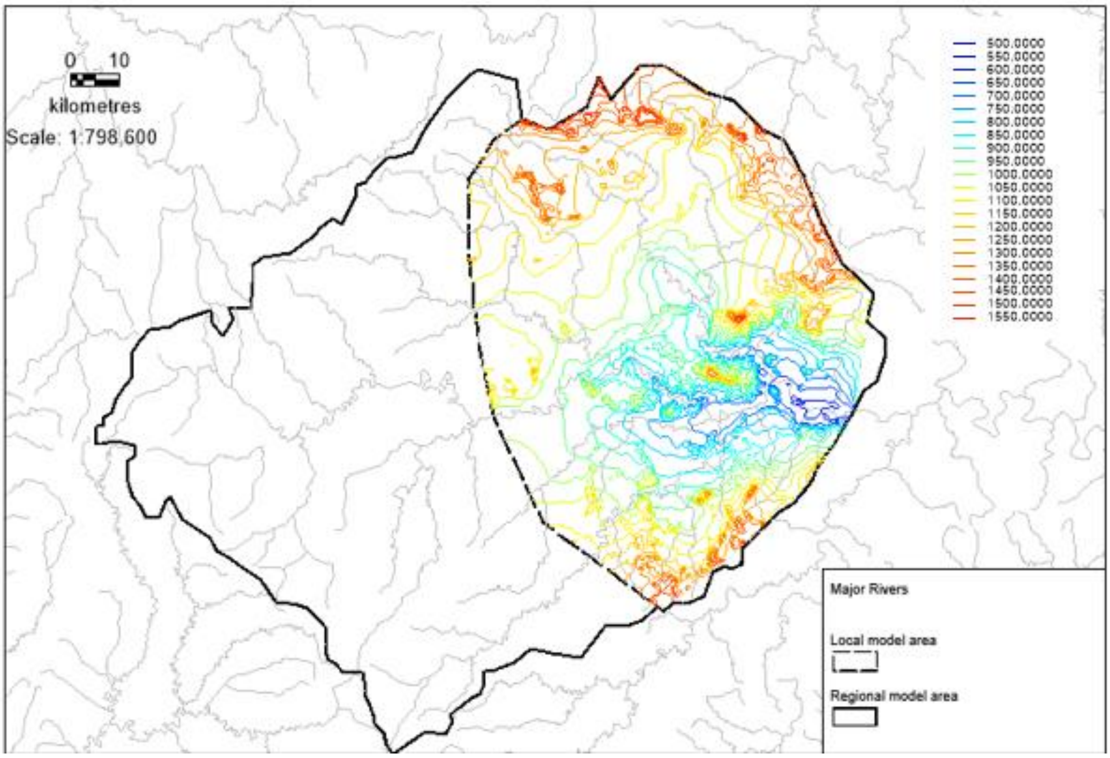


Figure 55 Simulated potential head map in the geological layers 80 meters below ground surface in the baseline scenario. Values are in meters above sea level

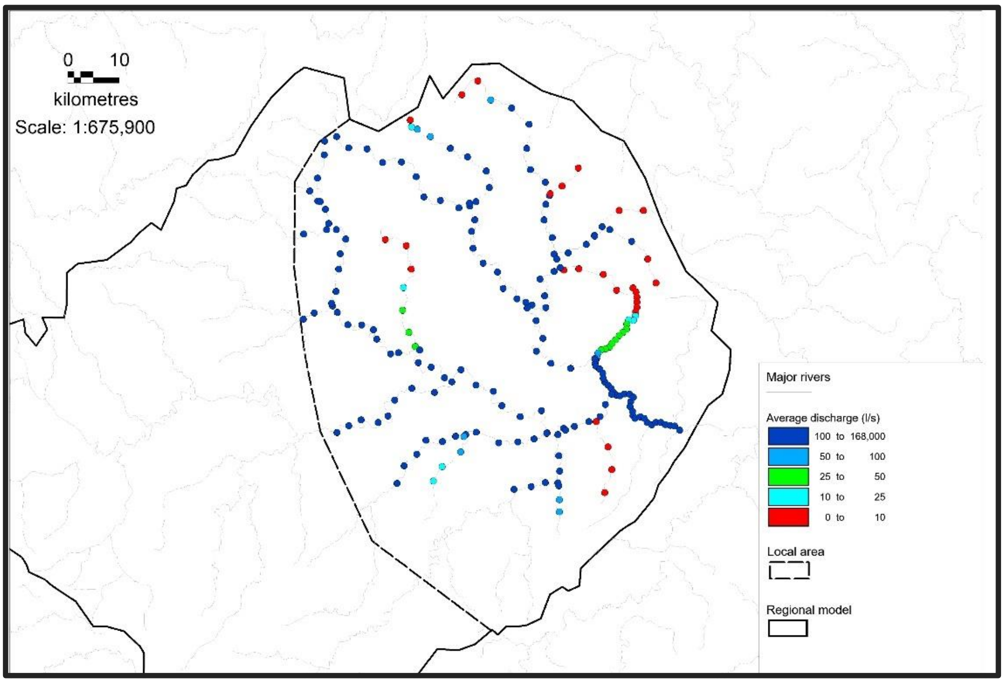


Figure 56 Average simulated discharge in model calculation discharge points

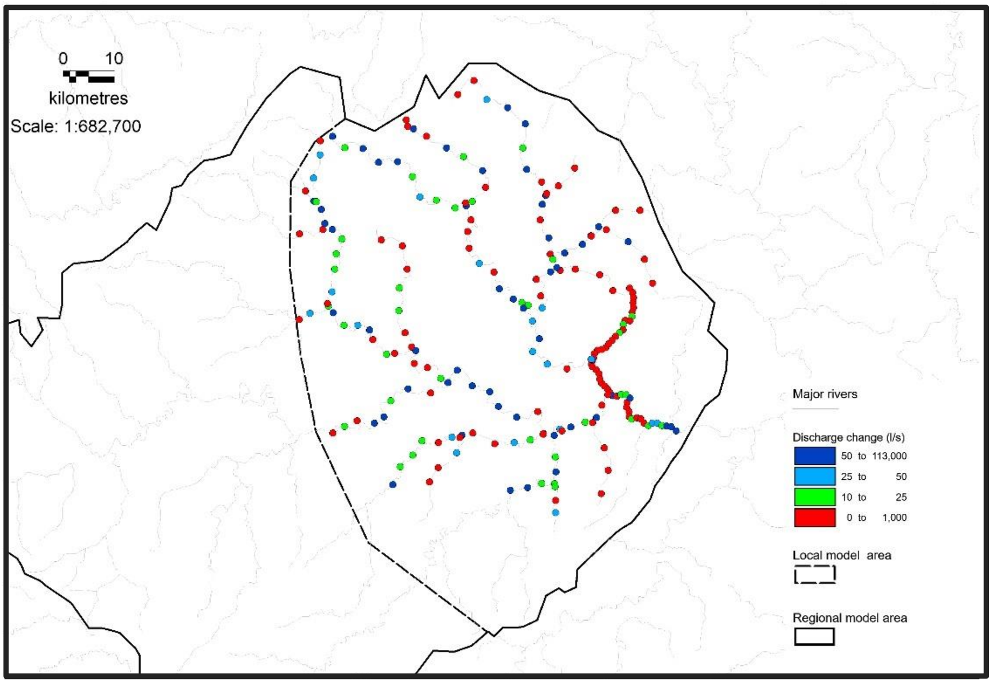


Figure 57 Simulated downstream increase in river discharge

7.2 Scenario 2

In scenario 2 the yellow targets shown on Figure 58 and Figure 59 were selected for well field simulation. These are a part of The Umgeni water primary targets shown on Figure 10. Most of the primary targets are within medium-high transmissivity areas. Moreover, the targets are located within areas with high groundwater recharge and within an area with a high density of faults, where a good contact between shallow and deeper groundwater zones is expected. Therefore, it was decided to use these as well field target in scenario 2.

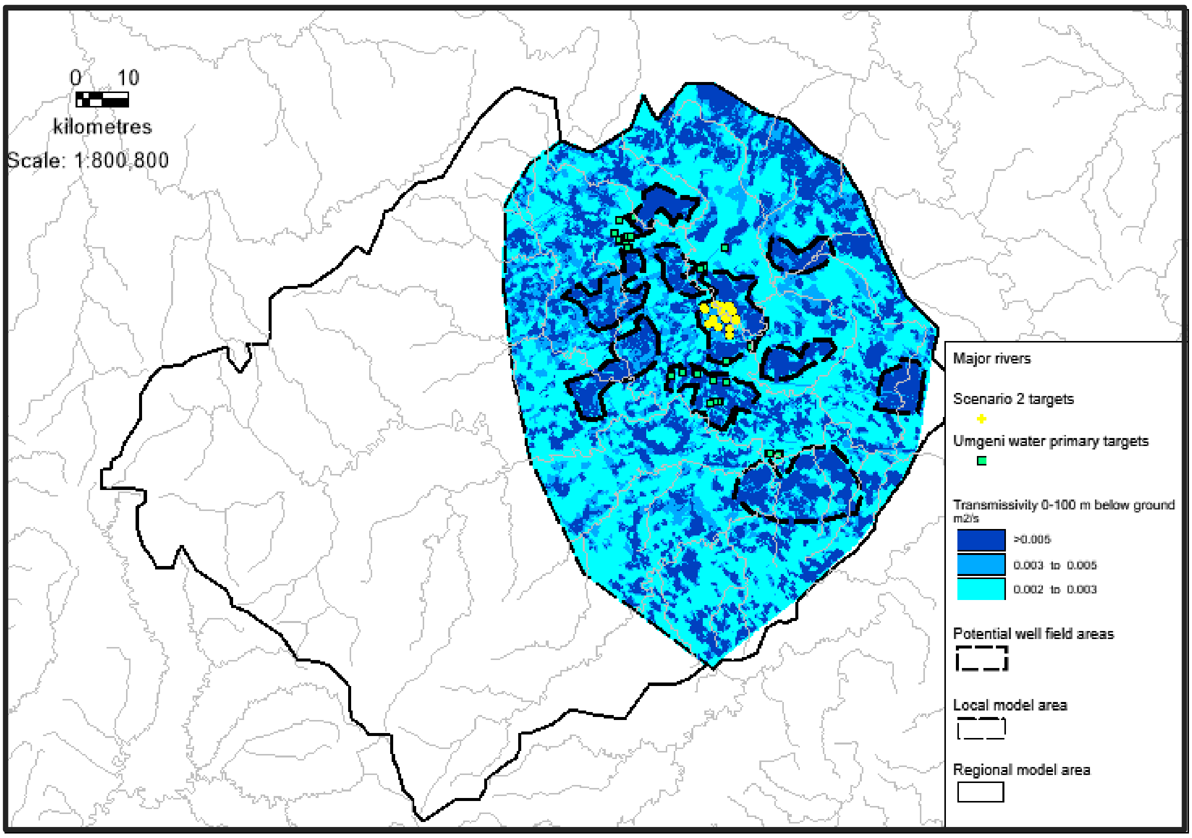


Figure 58 Scenario 2 targets

The main objectives in scenario 2 were to calculate how much groundwater that can be abstracted sustainably and to delineate the catchment area to the abstractions. The sustainable abstraction criterion used was that the simulated groundwater level at the wells should not be lowered to more than 50 meters below ground surface. The procedure for calculating the sustainable groundwater was as follow: A preliminary catchment was delineated, Figure 60, and the average groundwater recharge was calculated, equalling 12. 8 million m^3 per year or 23 mm/year as shown in Figure 61. As a first guess the sustainable groundwater abstraction was estimated to be 30% of the average recharge. Moreover, the wells were assumed drilled to a depth of 100 meters as an open borehole except a sealing in the upper part to avoid surface water running into the well. After the first iteration the simulated depth to the water table were extracted from the model and evaluated. If the groundwater were lowered to more than 50 meters below ground

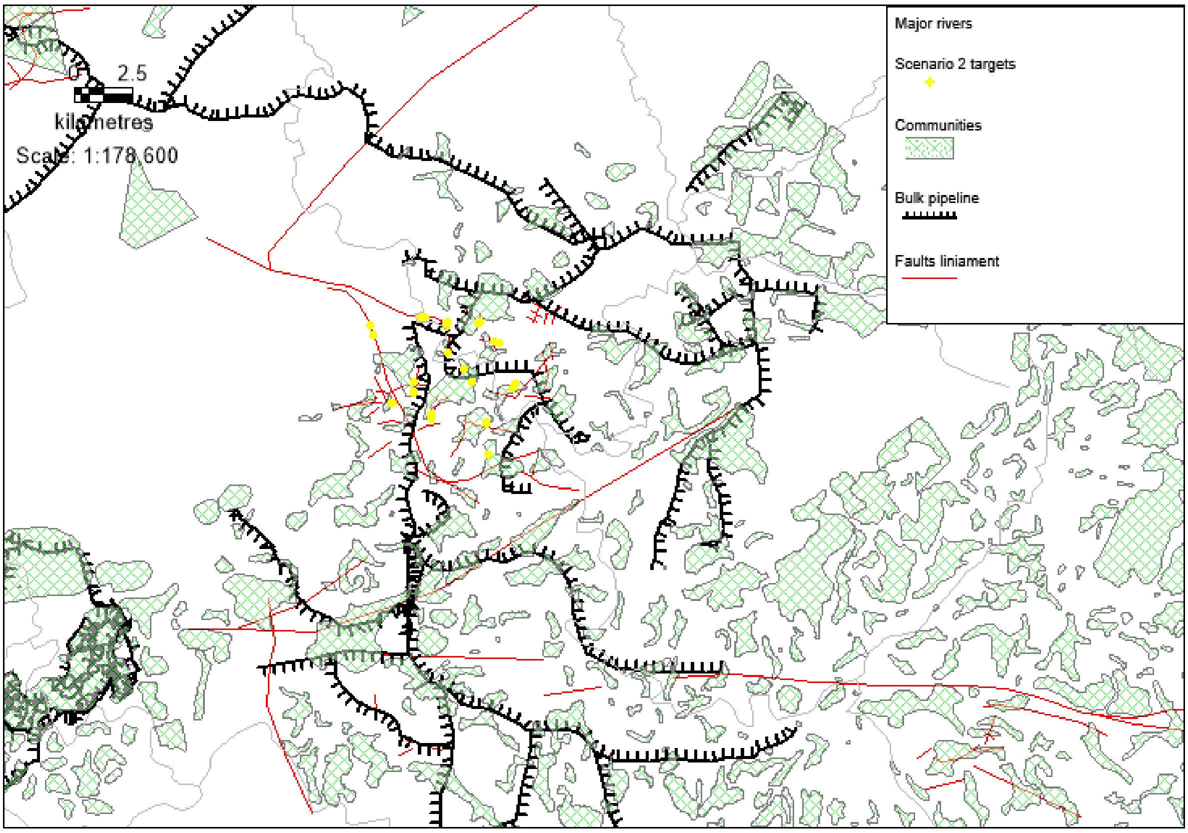


Figure 59 Scenario 2 targets located northeast of Ladysmith

surface, the abstraction was reduced from that specific target and increased in other target where the simulated groundwater table were higher

After four iterations a maximum sustainable groundwater abstraction was calculated to be approximately 4.9 million m^3 per year within the preliminary catchment, which corresponds to 38% of the recharge. Within the preliminary catchment there is only one registered well which is a schedule 1 borehole, so the impact from existing well is estimated to be very small. The abstraction distributed on individual targets are shown in Table 10 together with the simulated depth to the phreatic surface. The final abstraction distribution has been found by evaluating the simulated depth to the water table between each iteration. In some targets the simulated water table is just violating the criteria of a groundwater table maximum 50 meters below ground surface, while more can be abstracted at other targets. The model simulation error has not been taken into consideration in the determination of the sustainable yield, but of course there will be an uncertainty related to the model estimation of the depth to the water table. It is important to highlight that the calculated sustainable abstraction is for the whole “preliminary” catchment, which in this case has been associated to one big well field. It is recommended to distribute the abstraction on as many well as possible within the catchment to distribute the stress on the groundwater.

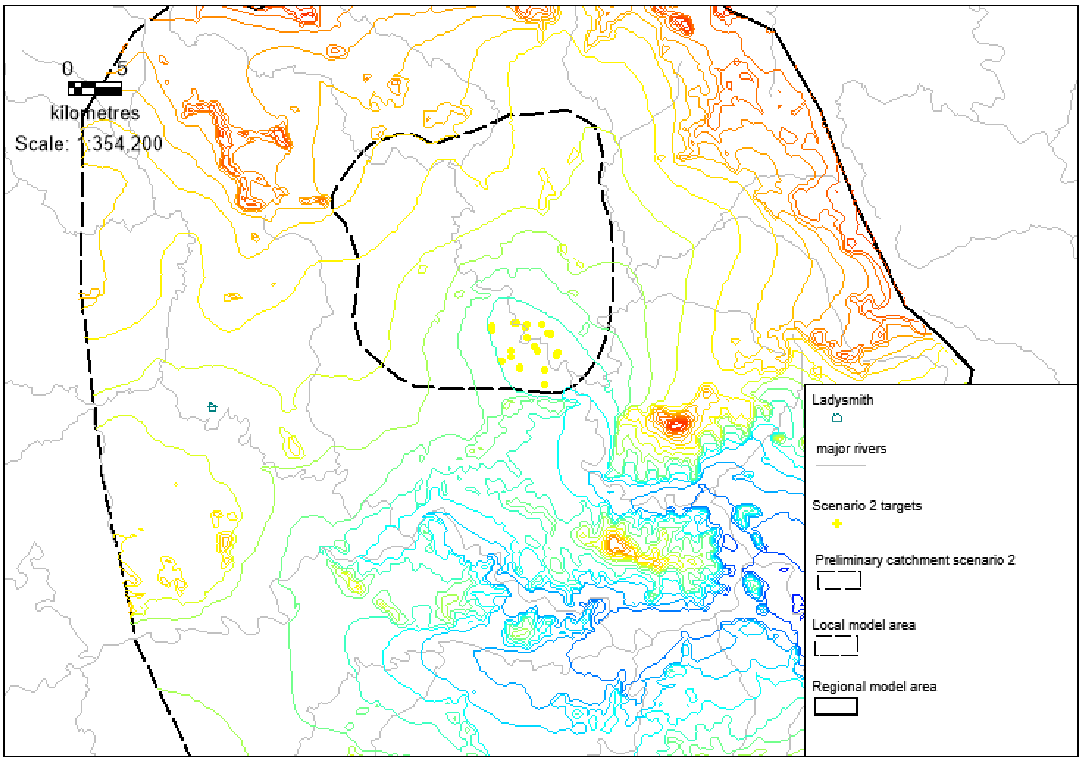
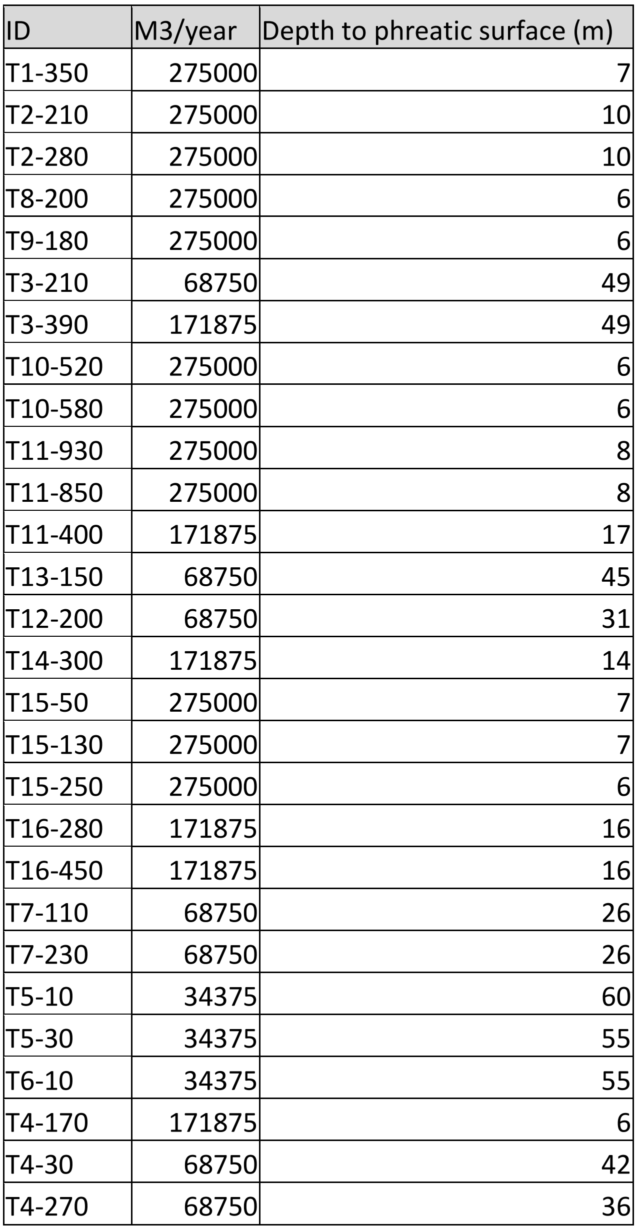


Figure 60 Delineation of preliminary catchment shown on simulated potential head map



ID	M3/year	Depth to phreatic surface (m)
T1-350	275000	7
T2-210	275000	10
T2-280	275000	10
T8-200	275000	6
T9-180	275000	6
T3-210	68750	49
T3-390	171875	49
T10-520	275000	6
T10-580	275000	6
T11-930	275000	8
T11-850	275000	8
T11-400	171875	17
T13-150	68750	45
T12-200	68750	31
T14-300	171875	14
T15-50	275000	7
T15-130	275000	7
T15-250	275000	6
T16-280	171875	16
T16-450	171875	16
T7-110	68750	26
T7-230	68750	26
T5-10	34375	60
T5-30	34375	55
T6-10	34375	55
T4-170	171875	6
T4-30	68750	42
T4-270	68750	36

Table 10 Final abstraction distributed on targets in scenario 2

By comparing Figure 61 and Figure 62 it can be seen that the groundwater abstraction is primarily taken from the river outflow and to a less degree subsurface groundwater exchange on the border of the preliminary catchment.

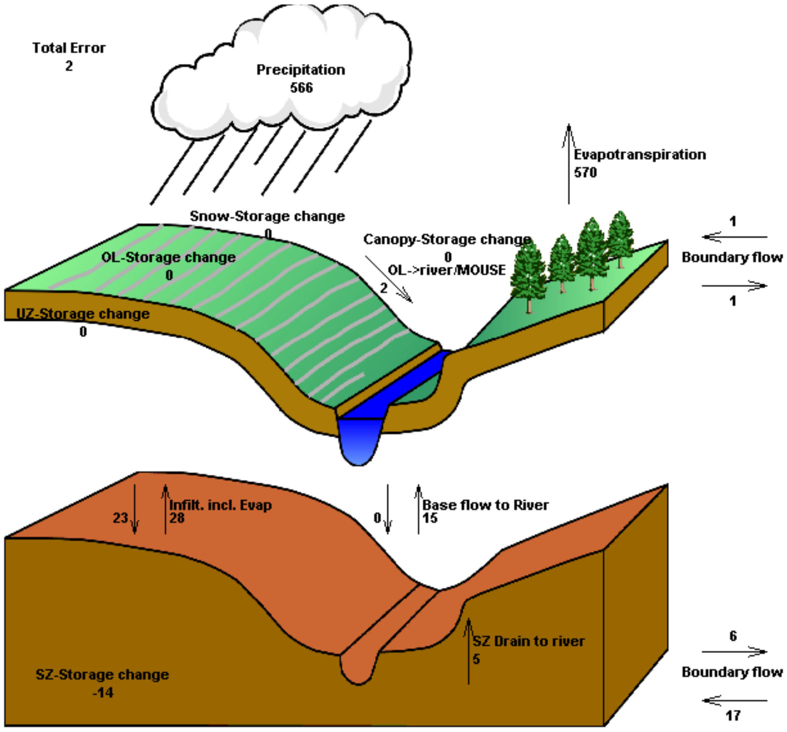


Figure 61 Average Water balance for preliminary catchment for the period 2008-2018 in scenario 1

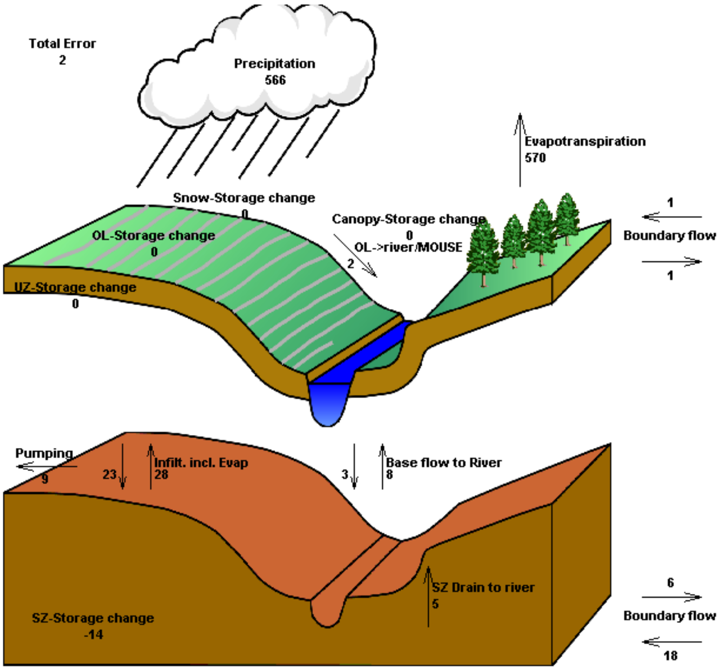


Figure 62 Average Water balance for preliminary catchment area for the period 2008-2018 in scenario 2

To calculate the groundwater catchment, it was necessary to reduce the number of simulation layers to obtain reasonable computational time. After several tests to make the particle tracking run, it was reduced to three simulation layers. The geological heterogeneity is still included but as part of larger simulation layers. To fully explore the impact of the aquifer heterogeneity, all model layers should be included in the particle tracking, which is recommended at a later stage, but requires very powerful computers.

The 200 years catchment area delineated by particle tracking is shown in Figure 63. Porosities were set to 0.1 for sandstone, 0.01 for shale and 0.03 for dolerite, which are commonly used values for effective porosities for these lithologies according to the literature, for example /3/. The catchment area is defined after the danish methodology with a 100 meters buffer and includes a 300-meter catchment zone around the well for local groundwater protection. In Denmark groundwater protection is not considered for groundwater older than 200 years. The area of the catchment is 300 km^2 and smaller than the preliminary estimated catchment which were 550 km^2. The reason for this is that the high recharge areas is concentrated in the southern part of the catchment area as shown on Figure 64 and not evenly distributed as assumed in the calculation of the preliminary catchment area. Groundwater recharge will also take place upstream the delineated catchment, but here the transport time is more than 200 years.

The simulated transport time for the groundwater is shown in Figure 65. The transport time varies from less than 10 years close to the targets to 200 years in the most upstream ends. In the main recharging areas shown in Figure 65, the average simulated transport time is 42 years.

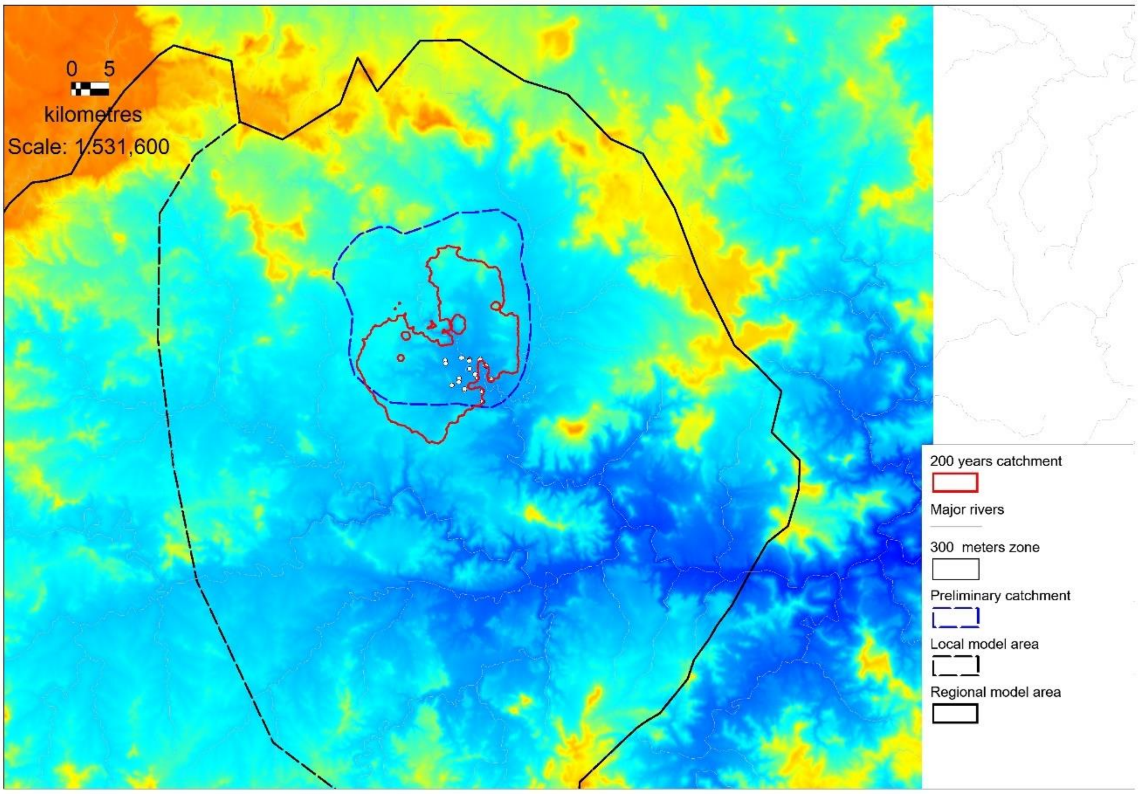


Figure 63 Catchment area scenario 2

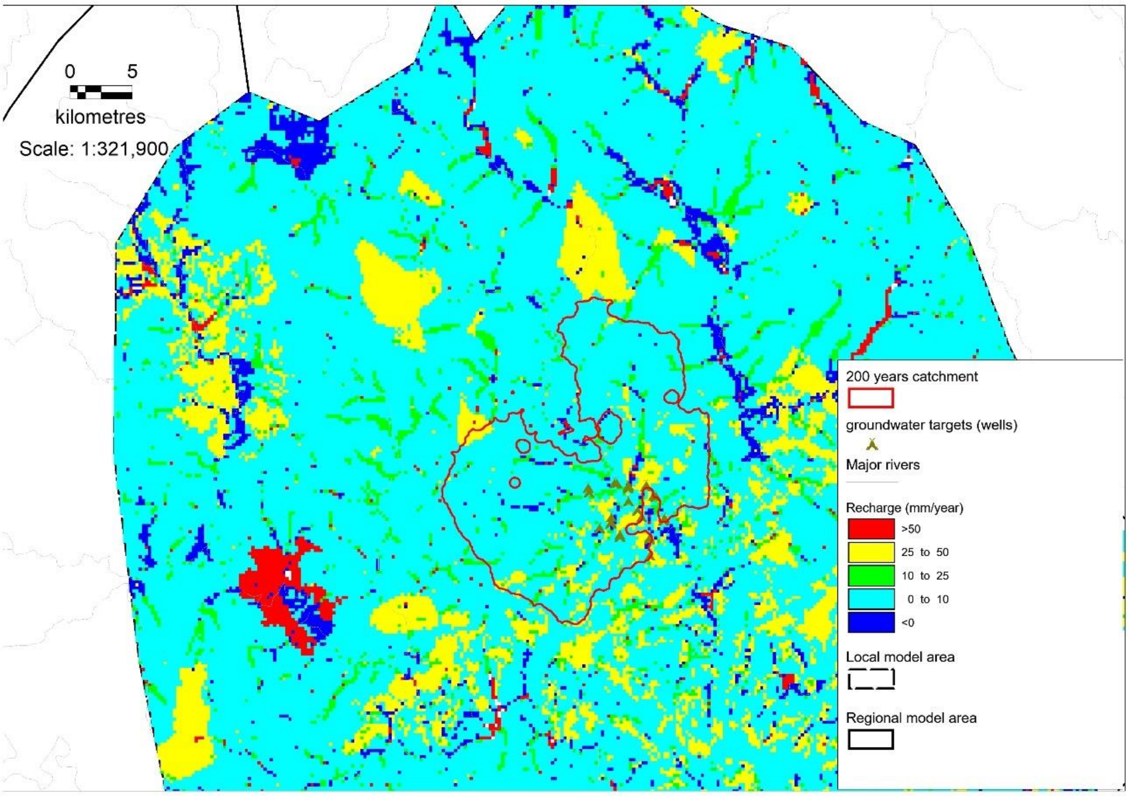


Figure 64 Local recharge distribution scenario 2

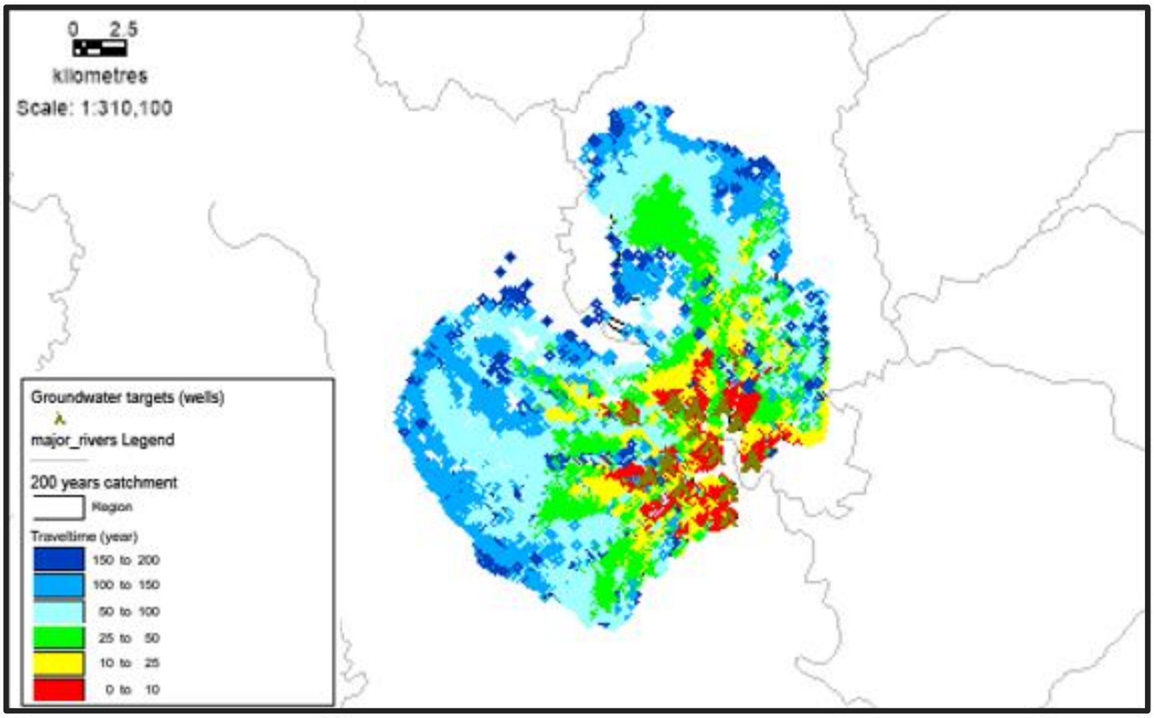


Figure 65 Simulated transport time to the groundwater targets

The simulated resulting drawdown is shown in Figure 66 for a simulation layer with top 80 meters below ground surface. The simulated potential head in the same layer is shown in Figure 55. The simulated drawdown in the layer is not straightforward due to the heterogeneous geology. The largest simulated drawdowns are closest to the groundwater targets, with simulated drawdowns up to 25 meters, and locally more than 25 meters. When comparing to the transmissivity fields the drawdown is largest east of the wellfields, where the transmissivity is highest indicating that most of the abstracted water will come from this area. Moreover, the faults also have impact on the distribution of the drawdown. The faults are implemented as positive hydraulic boundaries with a potentially high recharge reducing the drawdown extent. Moreover, the faults can act as a chimney between different parts of the aquifers, which gives a more complex drawdown picture than in a homogeneous geological environment. Therefore, fractures must be correctly mapped and implemented in the model to get reliable results.

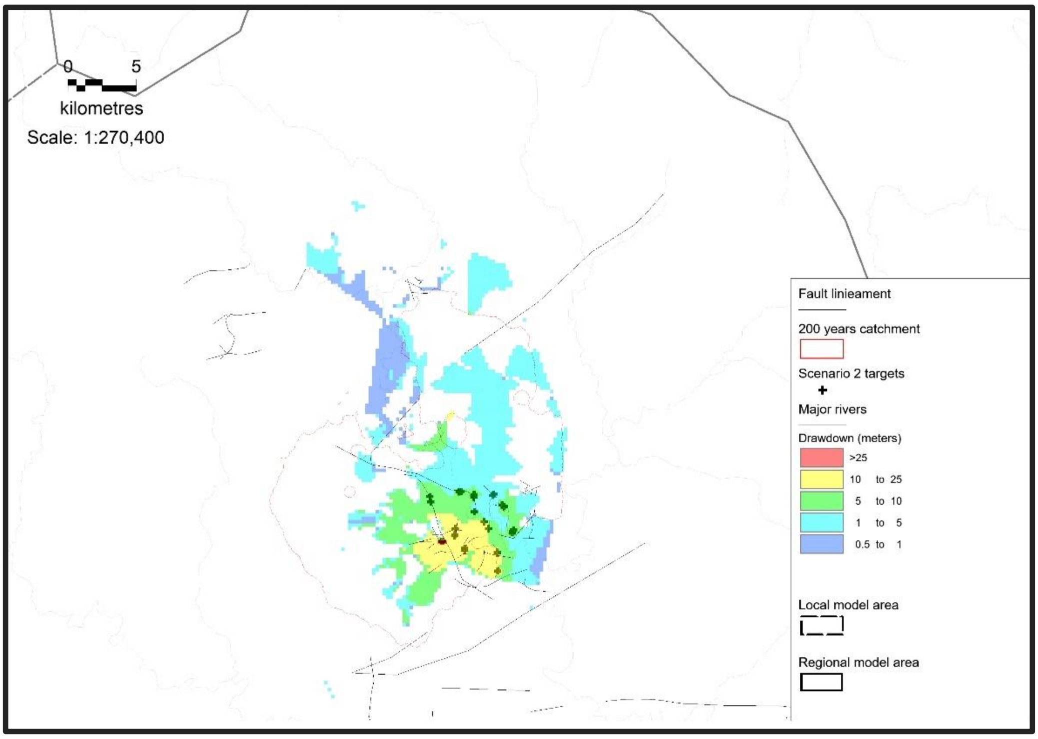


Figure 66 Simulated drawdown in simulation layer located 80 meters below ground surface

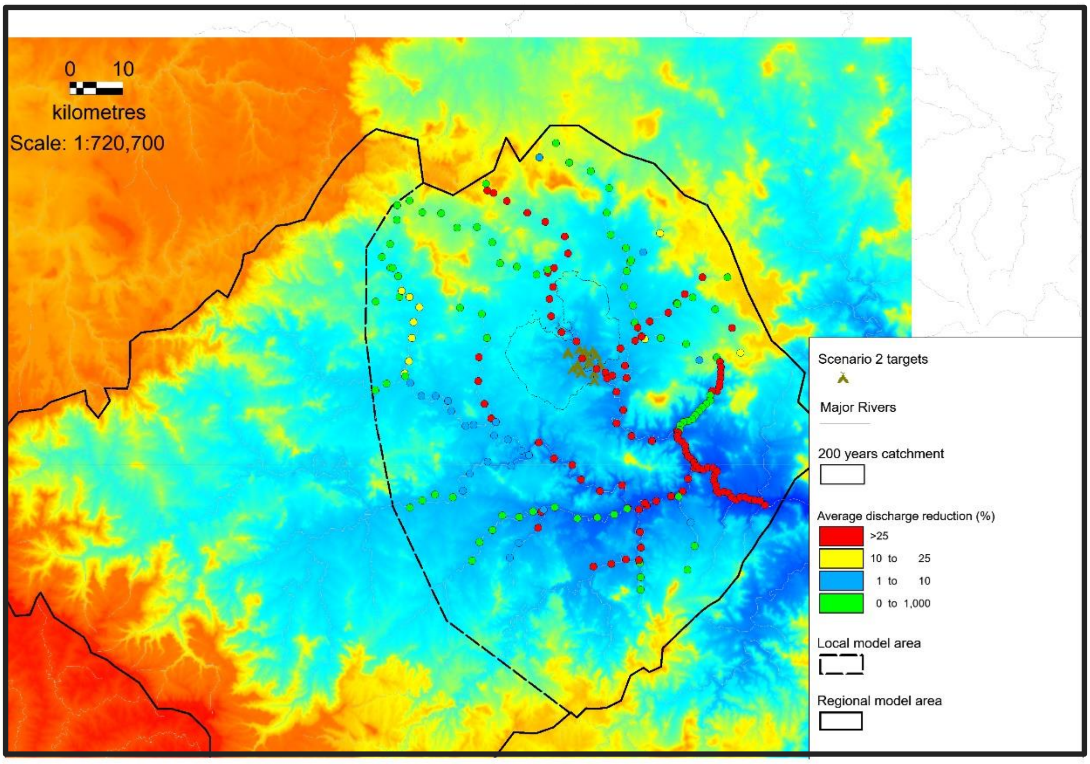


Figure 67 Discharge zones scenario 2

7.3 Scenario 3

In scenario 3 all Umgeni Water primary targets were selected initially for well field simulations. The selected targets are seen in Figure 68. The same methodology to calculate the sustainable groundwater abstraction were used as in scenario 2. Within the preliminary catchment shown on Figure 69 the average recharge was estimated to be approximately 27 million m^3 per year, and the sustainable groundwater abstraction was calculated to be approximately 8 million m^3 per year, corresponding to almost 30 % of the recharge. It was reached after 4 iterations with the distribution shown in Table 11. As in scenario 2 the sustainable criteria were that the simulated water table must be lowered more than 50 meters below ground surface for the individual targets/wells. During the iterations, 14 groundwater targets were excluded because it was impossible to meet the sustainable criteria.

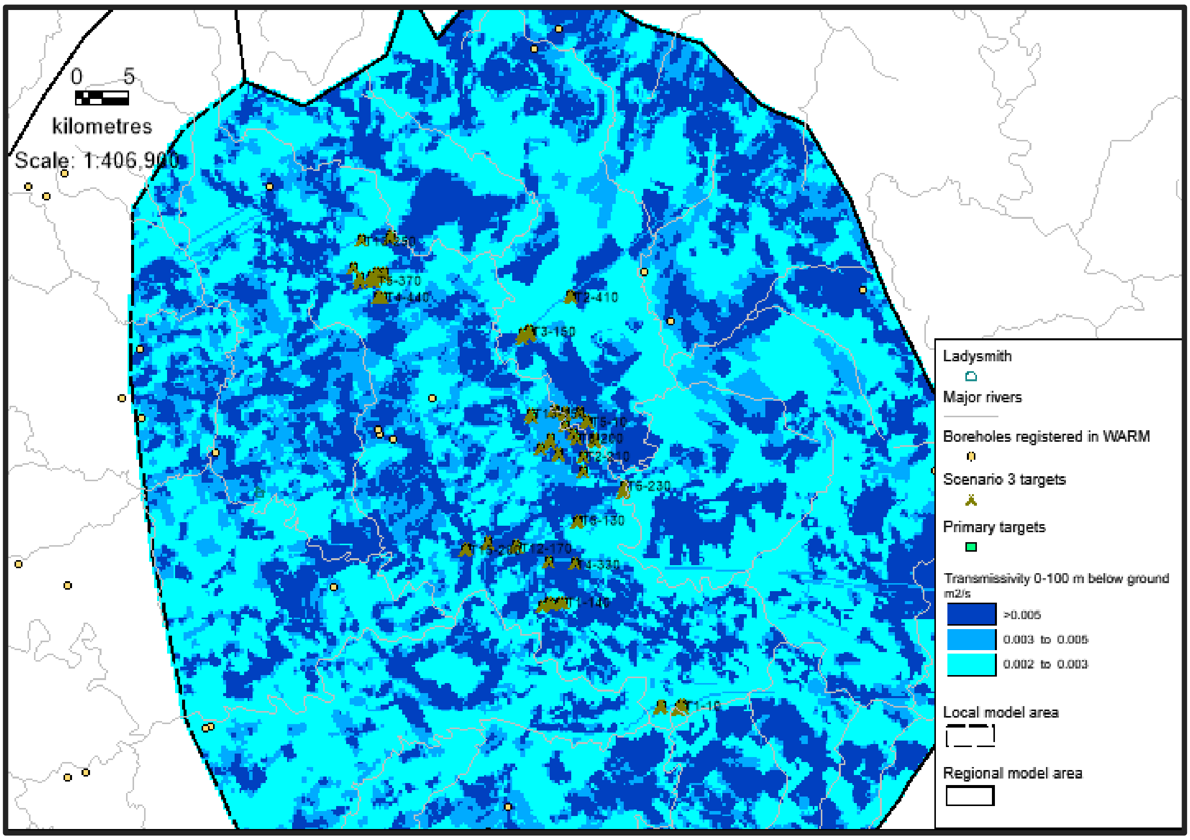


Figure 68 Scenario 3 targets

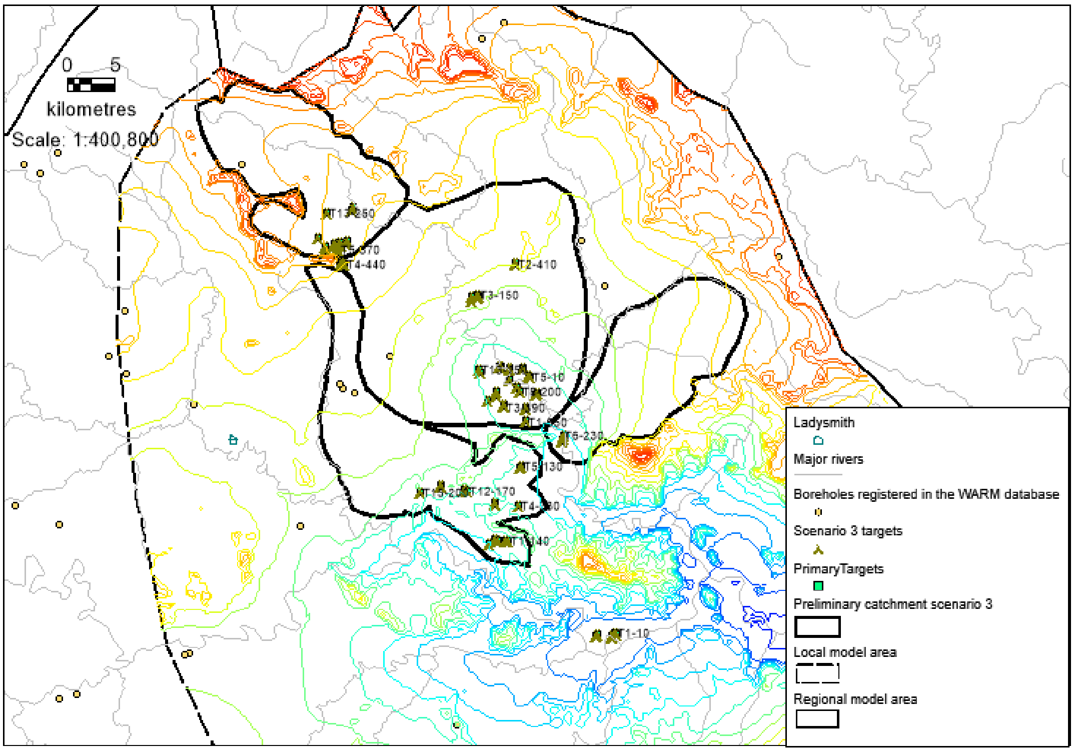


Figure 69 Preliminary catchment together shown on simulated potential head map

The final calculated 200 years catchment is shown in Figure 70. The total area is 600 km^2. The simulated transport time to the groundwater targets is show in Figure 71. The calculated travel time varies from less than 10 years to more than 200 years (outside the 200 years catchment) with an average of 36 years. To be able to simulate the abstraction catchment area it was necessary to simplify the model setup and reduce the number of simulation layers, so the horizontal fractures are not present by individual model layers in the particle simulations but included as part of thicker layers. This probably affect the uncertainty, but this has not been evaluated further.

ID	M3/year	ID	M3/year
T1-10	147697.2	T11-850	172313.4
T1-60	147697.2	T11-400	98464.8
T1-220	147697.2	T13-150	98464.8
T2-300	147697.2	T12-200	98464.8
T2-360	147697.2	T14-300	275000
T3-190	147697.2	T15-50	275000
T3-270	147697.2	T15-130	275000
T3-350	275000	T15-250	275000
T1-140	19692.96	T16-280	275000
T1-430	19692.96	T16-450	275000
T2-340	19692.96	T7-110	98464.8
T2-100	19692.96	T7-230	98464.8
T3-250	19692.96	T5-10	49232.4
T4-330	172313.4	T5-30	49232.4
T9-180	98464.8	T6-10	49232.4
T9-240	19692.96	T4-170	172313.4
T15-200	9846.48	T4-30	147697.2
T15-320	9846.48	T4-270	147697.2
T16-330	172313.4	T2-410	98464.8
T16-410	172313.4	T2-350	98464.8
T12-10	9846.48	T2-260	9846.48
T12-170	9846.48	T3-150	9846.48
T6-230	172313.4	T3-370	9846.48
T6-560	172313.4	T3-620	98464.8
T6-750	172313.4	T4--270	98464.8
T6-940	172313.4	T4-200	9846.48
T5-130	9846.48	T4-440	98464.8
T5-300	9846.48	T4-190	19692.96
T1-350	172313.4	T4-50	98464.8
T2-210	4915625	T5-370	9846.48
T2-280	275000	T5-210	19692.96
T8-200	275000	T7-130	98464.8
T9-180	275000	T7-340	19692.96
T3-210	98464.8	T8-330	19692.96
T3-390	275000	T2-390	9846.48
T10-520	275000	T1-360	9846.48
T10-580	275000	T2-20	9846.48
T2-130	9846.48	T11-140	9846.48
T1-20	172313.4	T13-250	172313.4
T9-0	9846.48	T14-80	172313.4
T9-430	172313.4	T15-180	172313.4
T11-930	98464.8		

Table 11 Scenario 3 targets with calculated abstraction rates

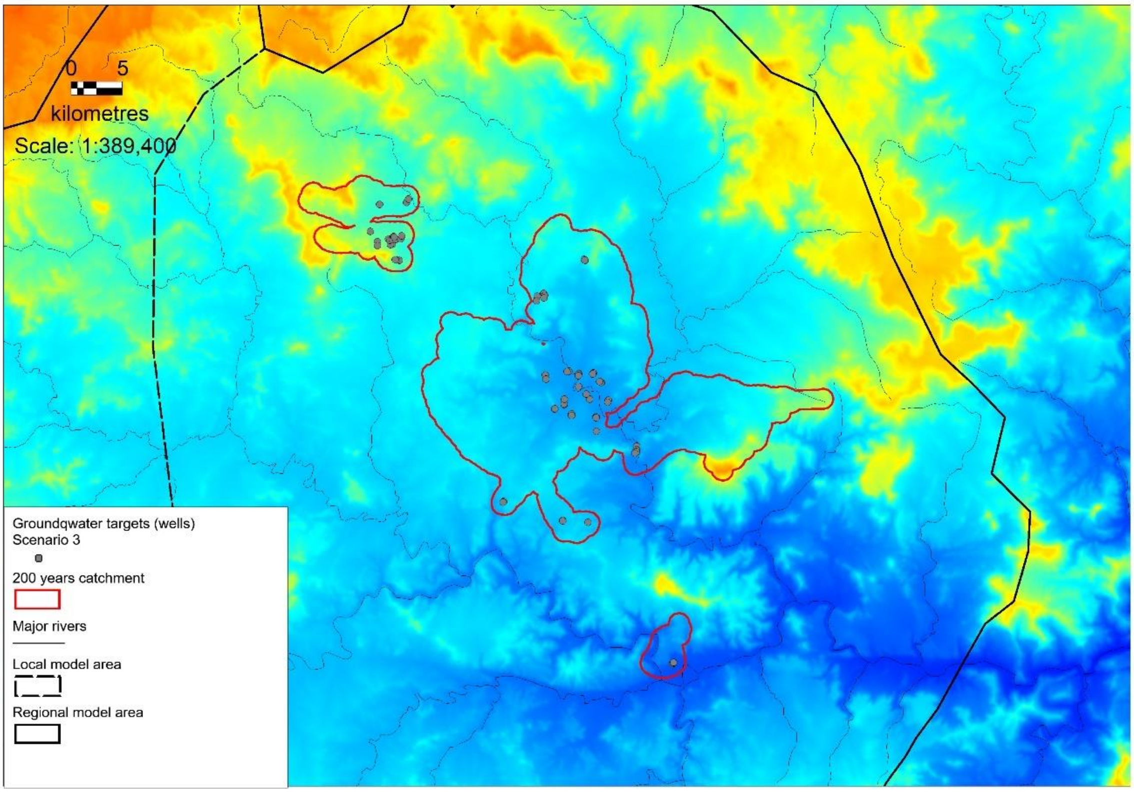


Figure 70 Delineation of 200 meters catchment for scenario 3

The simulated drawdown shown in Figure 72 is not straight forward to interpret. It seems like the drawdown distribution is controlled by the transmissivity distribution, the topography, and the high geological heterogeneity. The main groundwater flow takes places within limited high permeable zones, and the drawdown when groundwater abstraction is initiated can be distributed over a large area through the permeable horizons. Moreover, the elevated areas often have a higher transmissivity because of larger aquifer thickness which reduce the drawdown and the groundwater recharge is higher at the foothills of the mountains. Because of these effects the drawdown tends to sneak around the mountainous areas (Figure 73) giving the drawdown distribution a characteristic pattern. An important learning from this is that the fracture pattern is important to map both in low areas and elevated areas.

The biggest drawdowns are simulated around the wells, with simulated drawdowns locally above 25 meters.

By comparing Figure 74 and Figure 75 it can be seen that according to the simulations, the abstracted groundwater is mainly taken from river discharge and increased groundwater inflow into the area. Impacted river points are shown in Figure 76, and as it can be seen most of the river stretches in the central parts are impacted where a discharge reduction is simulated.

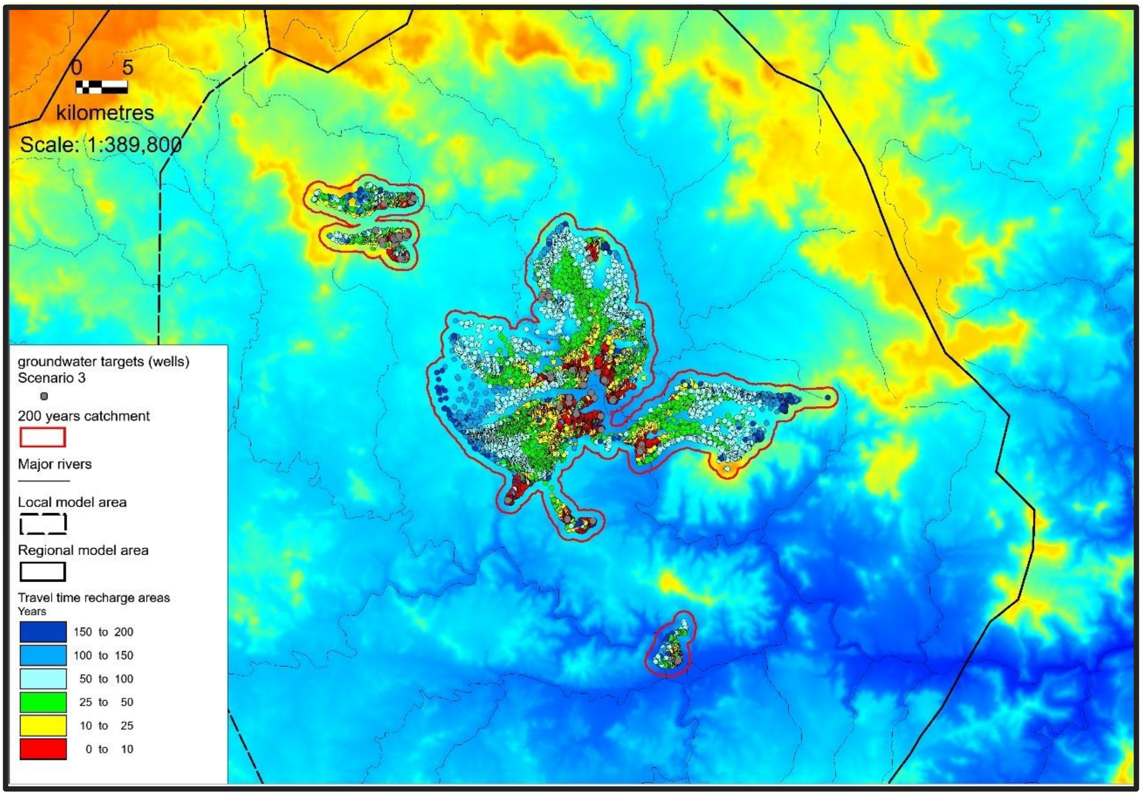


Figure 71 Travel time to groundwater targets from recharge areas

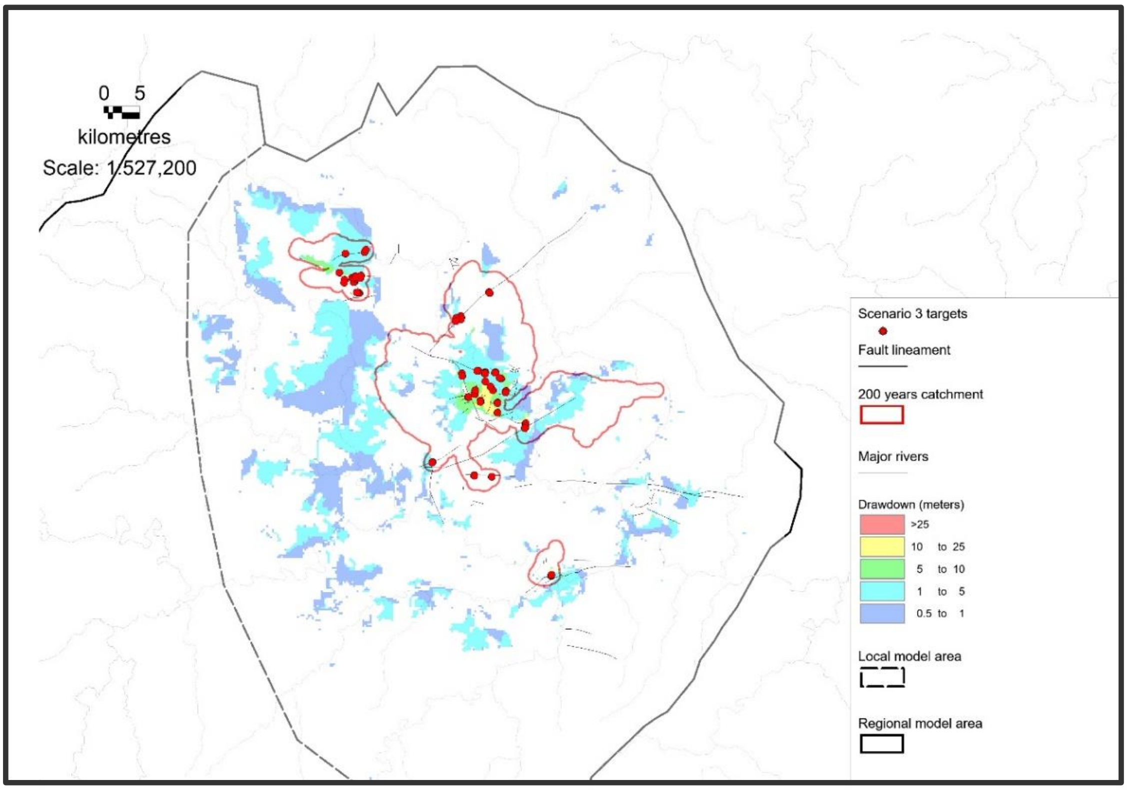


Figure 72 Simulated drawdown in simulation layer 80 meters below ground surface

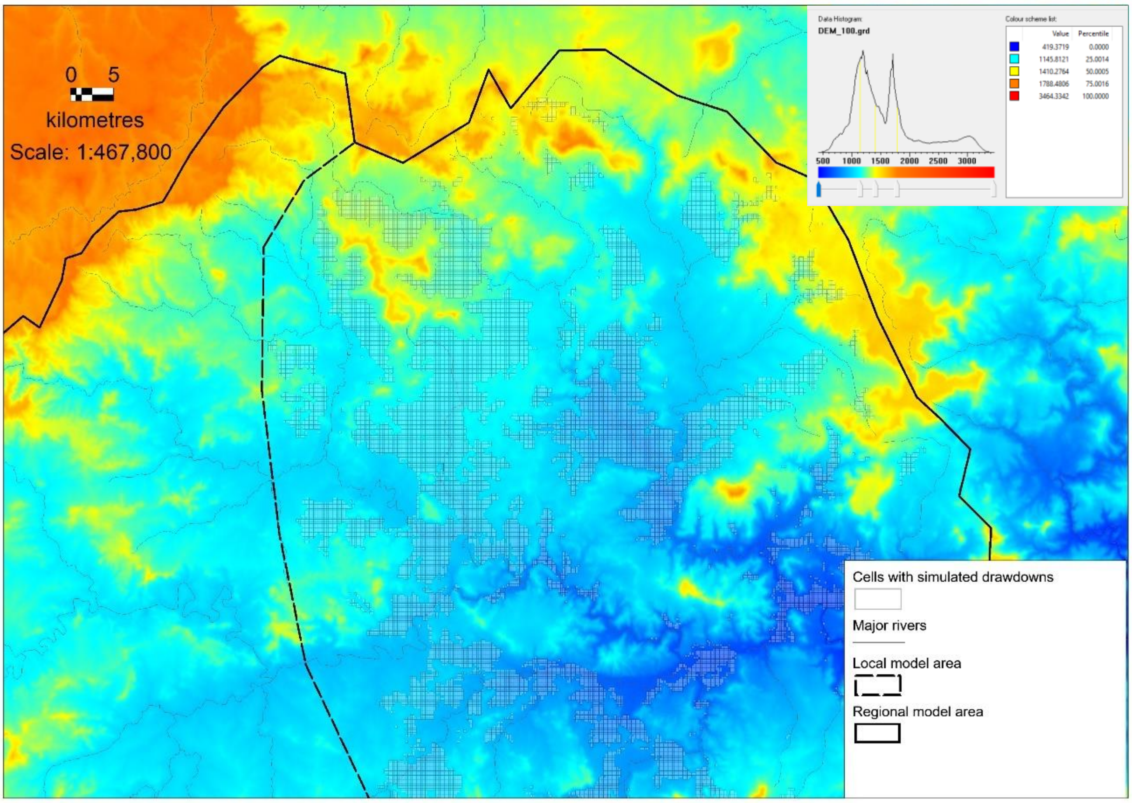


Figure 73 Cells with Simulated drawdown in simulation layer 80 meters below ground surface to illustrate drawdown distribution versus elevation

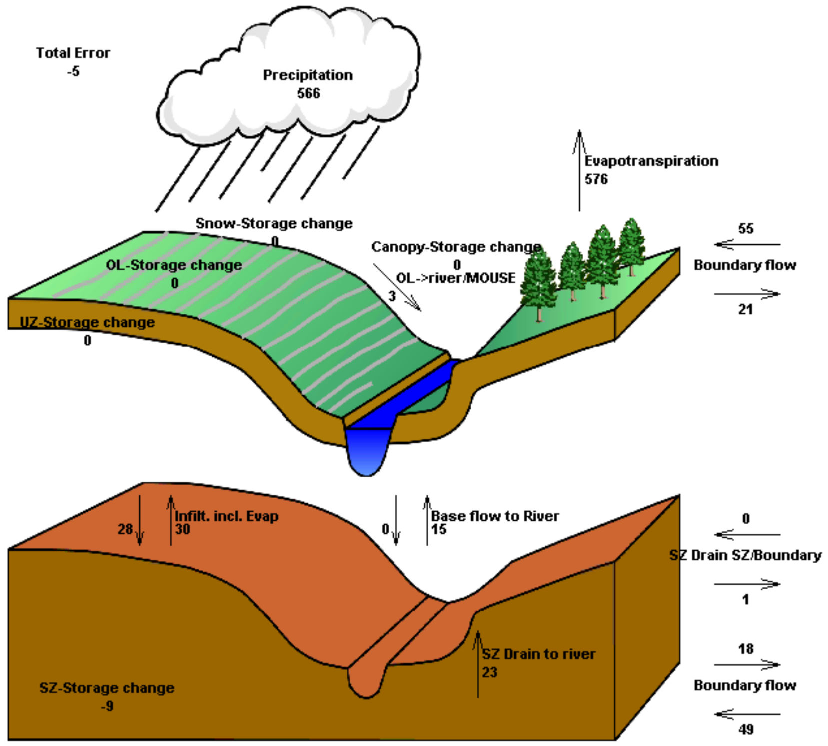


Figure 74 Average Water balance for preliminary catchment area for the period 2008-2018 in scenario 1

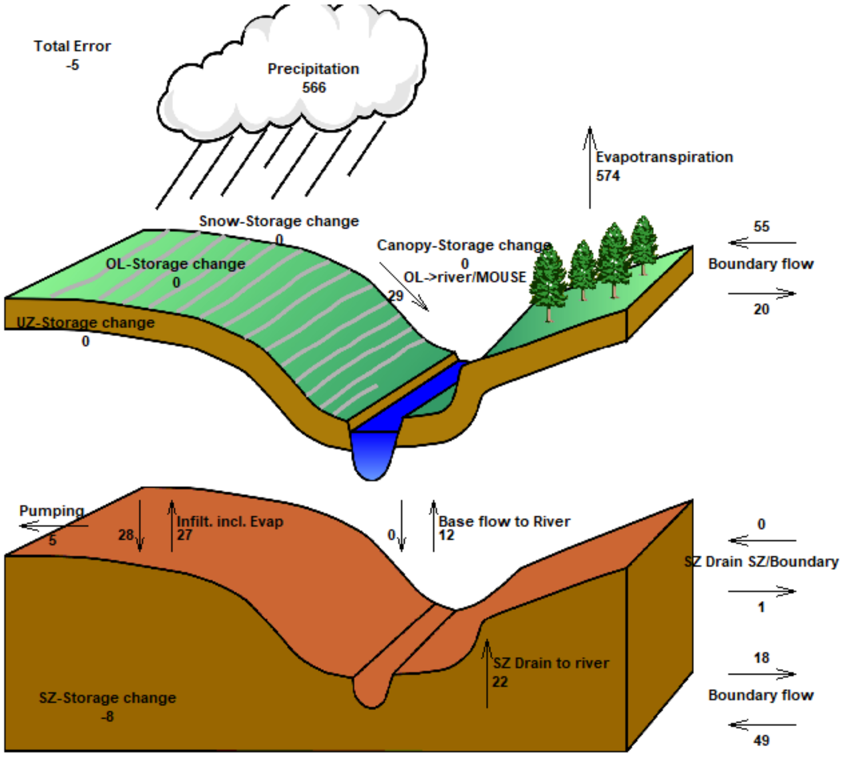


Figure 75 Average Water balance for preliminary catchment area for the period 2008-2018 in scenario 3

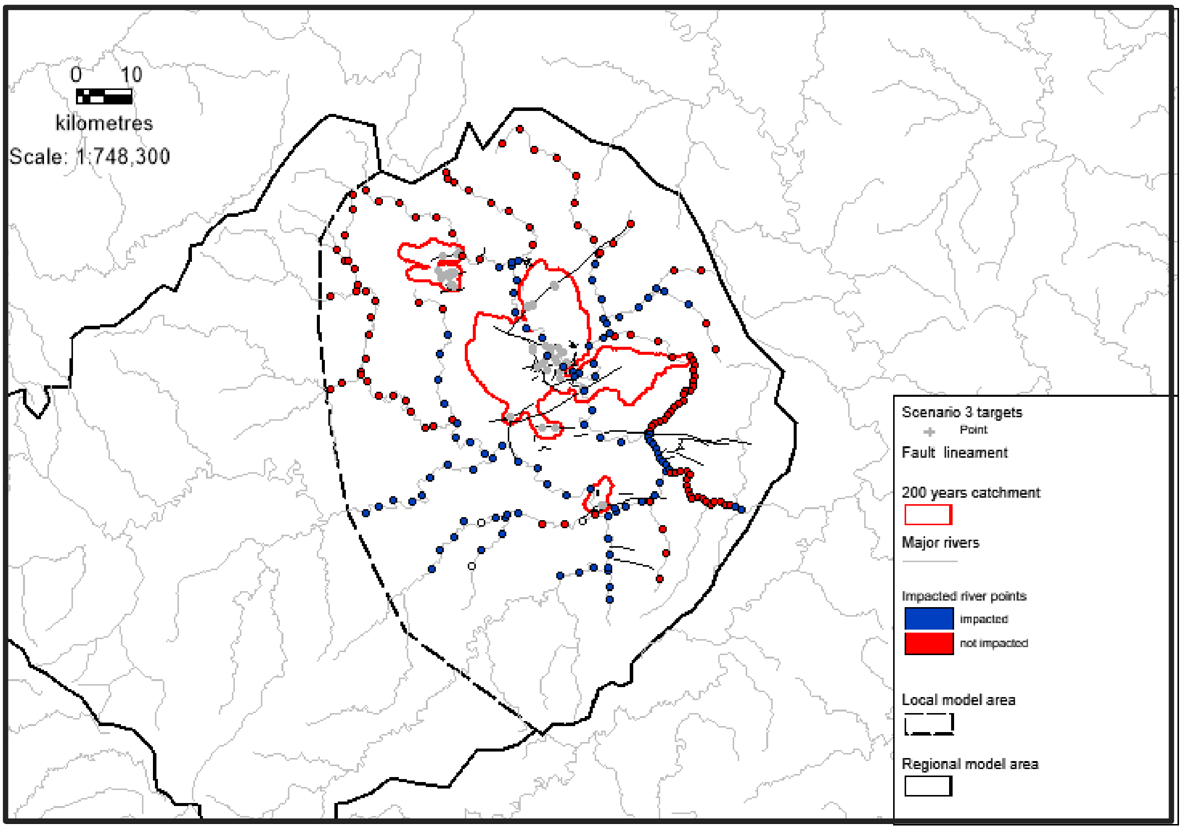


Figure 76 Impacted river points

8. CONCLUSIONS AND LEARNINGS

The most important term in the water balance for groundwater systems is the groundwater recharge, which depends on the actual climate and vegetation. The climate data, i.e. precipitation and potential evaporation, determines the potential recharge, while the actual recharge depends on the water availability and vegetation types. Furthermore, depending on the surface properties such as the infiltration capacity and slope, a fraction of the precipitation can be converted to overland flow that flows to low-lying areas and infiltrates – a process especially important in mountainous/hilly areas. Using an integrated model, as the MIKE SHE model system used in the Ladysmith study, these interactions can be described, resulting in a more precise estimate of actual recharge and its spatial distribution compared to other stand-alone approaches. It is therefore recommended that future assessments are also undertaking by an integrated modelling approach. Compared to the present study, the recharge estimate can be improved by utilising site-specific data vegetation, which was not applied here. It is further recommended that the model is run transient and thus describes the temporal variations in input data, groundwater, and river discharge, as experiences from Danish model studies clearly indicate that this provides the most robust results.

Climate input to the model has been provided from two climate station in the area. Compared to the area size, this is few stations to resolve the spatial variation, especially in the mountain areas, as precipitation is known to vary with elevation. Due to the large topographical variations in South Africa, it is recommended to improve the spatial resolution of climate data. The best approach would be to extent the climate monitoring net. An approach that can be utilised already now is to use a more sophisticated scheme in the inter- and extrapolation of station data in which the local elevation is incorporated.

The unsaturated part of the subsurface has been described by the water balance model two-layers. Here it is assumed that water above the field capacity infiltrates directly to the saturated zone, with no delay. In areas with a deep unsaturated zone recharge to the saturated zone can be significantly delayed violating the assumptions of the two-layer model. Well capture zones are commonly delineated based on 200 years travel time. Under such conditions the delay in the saturated zone is often negligible. However, in some cases it may be important, and other solutions can thus be tested like the Richard equation or gravity, which both comes with an additional computational burden. It is thus recommended, that the importance of the travel time in the unsaturated zone is evaluated prior to a model study, from which the appropriate unsaturated zone module is selected. An intermediate step can be the combination of the two-layer model and a simple analytical solution to estimate the additional UZ-travel time.

A complex geology/hydrostratigraphy is found in the study area and likely in other parts of South Africa. The voxel model provides a flexible approach for resolving such complex systems. Furthermore, the concept allows, to some extent, to represent faults, fractures, and dykes, which cannot be included in standard layered model interpretations. However, as also noted for the development of the geological model /5/, the large study area dictated the maximum model resolution, which for the hydrological model was a horizontal discretisation of 67.5m, where the vertical layers similarly had to be reduced in order to obtain simulation times that were practical feasible. With a coarse resolution, part of the aquifer heterogeneity is inherently lost. This is of high importance, especially for the representation on faults, fractures, and dykes that can have a profound importance on groundwater flow and drawdowns related to abstractions in the area. In accordance with the recommendations on the geological modelling, it is recommended that future detailed model studies are carried out for a smaller area than in the present study, to allow a better representation of aquifer heterogeneity. As robust boundary conditions may be difficult to establish in a heterogenic environment, the combined use of a larger scale/regional model and detailed models is further recommended, where the larger scale model is used to provide boundary conditions.

A prerequisite for the inclusion of faults etc. is that they are mapped, as described in the recommendations for the geological modelling. However, the mapping of a fault or similar, does not provide information on whether they act as positive or negative hydraulic boundaries. This may in some cases by inferred from other data, such as groundwater head data. Otherwise it is recommended that the mapping of faults and similar close to well-fields/planned well-fields is followed by pump test to evaluate the hydraulic properties.

Observation data on groundwater heads and streamflow is basis for model calibration, where the model's ability to reproduce the natural system is evaluated by comparing observed and simulated values. A challenge in this respect has been the general sparse data on groundwater head, especially newer data and time series, in combination with the borehole construction dominated by open boreholes. Measured groundwater heads therefore often represent an average of several geological units or water strikes. The groundwater heads are thus not associated to specific aquifers/levels and possibly vertical hydraulic gradients cannot be discerned. To provide a better basis for future calibration it is therefore recommended that time series of groundwater heads is expanded by either utilising existing wells and/or installing new wells. Furthermore, the new wells should be designed with smaller depth specific intakes, possible several in each well.

Groundwater pumping may have a negative impact on the surface water system, such as lakes and rivers. Understanding the interaction between groundwater and surface water is consequently required in integrated water management. In the Ladysmith study, the rivers were included, but as no information on the river cross-sections were available, these were estimated by an automated approach from the topography and assumptions on width. With no knowledge of the true river depths the correct exchange between the groundwater and river cannot be guaranteed. Furthermore, in the representation of streams for Danish condition, evapotranspiration from free water surfaces in lakes and rivers are considered negligible and not included. This may not be a valid assumption for South Africa. The recommendation is thus to improve the knowledge and representation of the river systems in future model setups, which include the collection of river data (measurements or possible estimated from satellite data). Furthermore, large structures and dam operations should be included in the model where relevant.

An evaluation of model performance has been developed for modelling in the Danish groundwater mapping programme, based to Danish conditions. These were similarly used in the evaluation of the Ladysmith model, but given the large differences in observed groundwater heads, mainly controlled by topographic variations, it is recommended that these criteria are re-evaluated and adjusted to South African conditions.

9. REFERENCES

/1/ 2018: Groundwater Resource Assessment and Development within the uThukela District Municipality (Version 1.1)

/2/ DWS: Warm database

/3/ Mohala H. 2014: Effects of porosity on strength of sandstones (Hammenskraal and Waterberg)

/4/ https://manuals.mikepoweredbydhi.help/2017/MIKE_SHE.htm

/5/ Ramboll 2021: Case study on geological modelling – Ladysmith, South Africa

APPENDIX 1
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