

Golder Associates (Pty) Ltd

Vaal Gamagara SD1 Area Numerical Groundwater Flow Model Report

Project Number: Delh.2013.006-15



WATER SYSTEMS MODELLING



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1. INTRODUCTION

1.1. BACKGROUND

Delta H (Delta-H Water System Modelling PTY Ltd) has been appointed by Golder Associates Pty Ltd to develop a numerical groundwater flow model for the Vaal Gamagara (SD1) area to assess potential impact of the proposed well field on the regional groundwater flow, aquifer recharge and discharge.

1.2. GROUNDWATER MODELLING OBJECTIVES

The objectives of the current project are to:

- Develop and calibrate a three-dimensional regional numerical groundwater model quantifying the elements of the conceptual model as put forward by Golder Associates which 1) characterised the geological setting, 2) quantified and delineated areas of recharge, 3) established the influence of regional structural features (i.e. dykes) on groundwater movement, including the role of fracture zones acting as preferential groundwater flow paths and 4) established the aquifer hydraulic properties (i.e. transmissivity and storativity values).
- Apply the numerical groundwater flow model to calculate the impact of the proposed well field on groundwater flow, aquifer recharge and discharge, and the elevation of the water table.
- Develop recommendations to address any shortcomings and data knowledge gaps that need to be addressed in order to improve on the future calibration of the groundwater model and to verify the long-term predictions made in terms of groundwater flow.
- Delineate aquifer protection zones according to best national practice as outlined by the Department of Water Affairs.

1.3. DATA SOURCES AND DEFICIENCIES

The development of the numerical groundwater flow model was based on the following information and data made available to the project team by Golder Associates in 2013/2014:

- Regional geological map
- River courses (shapefiles)
- Digital elevation data (90m x 90m grid, SRTM data)
- Groundwater piezometric (10 m) contours
- Groundwater abstraction rate data (2013) for existing boreholes
- Proposed (recommended) abstraction rates for the proposed SD1 well fields.
- Water level data
 - Static and continuous monitoring data
- Spring (flow) discharge rates
- Aeromagnetic data with inferred dykes and faults (including published dykes and faults)
- Groundwater recharge zones
- Proposed model domain

2. CONCEPTUAL MODEL

2.1. GEOLOGY

Golder Associates developed a comprehensive conceptual understanding of the dolomitic and hard rock aquifers underlying the Vaal Gamagara SD1 region. The data gathered during the intrusive investigation (i.e. drilling and pumping test) and the evaluation of other available data has been used to develop a hydrogeological conceptual model for the area, which forms the basis for the numerical modelling and is summarised below.

The hydrogeology of the SD1 region is closely linked to the nature and distribution of the geological units, structures and dykes that influence the flow of groundwater. The surface geology of the SD1 region is presented in Figure 1. The geology consists mainly of dolomites of the Ghaap Plateau Formation in the Campbell Group and of Banded Iron(stone) Formation (BIF) of the Asbestos Hills Subgroup in the Griquatown Group. The outcropping Asbestos Hill BIF forms a topographical high along the western edge of the model domain and represents a regional recharge zone.

The bedrock geology is for parts of the study area concealed by the partially consolidated sediments of the Kalahari Group, and the Quaternary age superficial sand cover. The Kalahari Formation consists of calcrete, gravel and clay beds. Where the superficial cover becomes thin and patchy large areas of bedrock are exposed especially in the northern parts of the study area. The bedrock consists of dolomite and dolomitic limestone, with chert bands and almost pure lenses of limestone. The purity of limestone has led to its exploitation and the Idwala limestone quarry is one of many mines occurring in the region.

Numerous intrusive dykes (mainly magnetic with some low to non-magnetic) occur in the area, but seldom outcrop. Several intrusive dykes, with low to impervious hydraulic conductivity, compartmentalize the dolomite aquifer. The dyke/bedrock contact zones itself represent on the other hand preferential groundwater flow paths. The dykes act near surface as aquitards, restricting lateral water flow. At depth the dykes become fresh rocks and act as aquicludes, preventing water flow across it.

2.1. HYDROLOGY

The general hydrology (surface water drainages) of the study area is depicted in Figure 1. The average annual rainfall varies from 340 mm on the open flats to 490 mm over the Kuruman Hills and falls predominantly in the summer month during isolated thunderstorms. The higher rainfall over the Kuruman Hills is due to the orographic and thermal effects of the hills. In the study area, numerous non-perennial streams collect the runoff from the Kuruman Hills and flow westward where they tend to disappear in the Kalahari sands. The two main drainages namely the Steenbok River and the Klein-Riet River drain towards the east.

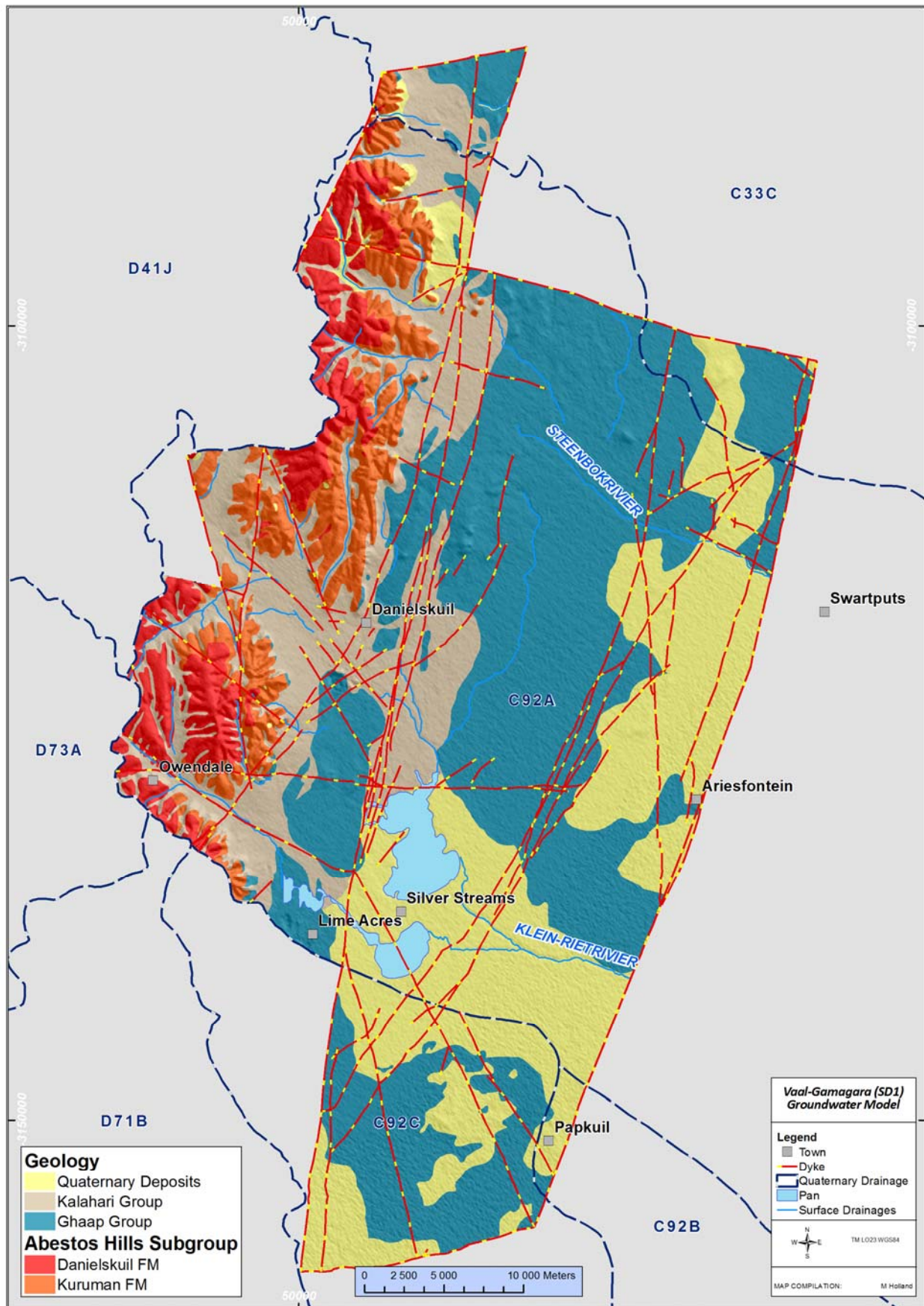


Figure 1: Geological Setting of the SD1 region.

2.2. AQUIFER SYSTEMS

The Vaal Gamagara (SD1) region is characterised by a number of productive aquifer units, represented by different hydraulic parameters and groundwater potentials. The following aquifers are present in the different geological formations:

- Intergranular (Kalahari Sediments) (Unconfined aquifer)
 - The calcrete with relatively low permeability retards and restricts the movement of water, but acts as a storage unit.
- Weathered and fractured (Semi-confined to confined aquifer)
 - The weathered and fractured BIF bedrock aquifer is quite productive and supports borehole blow yields of over 5 l/s. The BIF aquifer and underlying dolomite aquifer can be regarded as one hydraulic unit or aquifer system.
- Karst dolomite bedrock aquifers (Unconfined to confined aquifer)
 - The karst aquifers associated with the Ghaap Plateau (dolomite) Formations are highly productive with abstraction rates of high yielding production boreholes exceeding 40 l/s (for 24 hours per day).).

2.3. GROUNDWATER LEVELS AND FLOW DIRECTIONS

Utilising a total of 373 measured groundwater table elevations, Delta H established the correlation between surface topography and elevation of the hydraulic head (Figure 2) for the wider Vaal Gamagara (SD1) area. The water table elevations measured are indicative of the free water table (with no pressure) and the hydraulic head (sum of pressure, elevation and negligible velocity head). The hydraulic head only represents for unconfined aquifers the free water table, whereas it represents the potentiometric surface for confined aquifers.

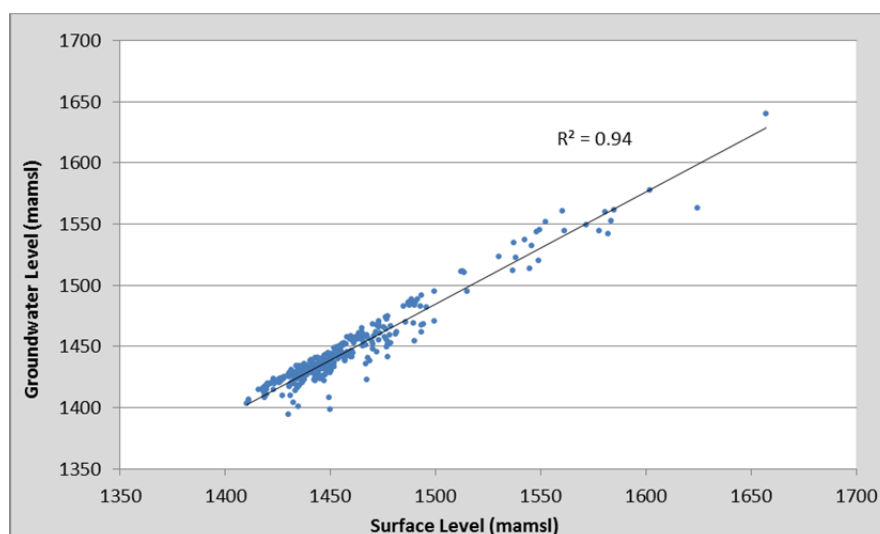


Figure 2: Correlation between surface topography and potentiometric heads.

A good correlation ($R^2=0.94$) between absolute surface and hydraulic head elevations in m above mean sea level (mamsl) is recognised for the SD1 area. The potentiometric surface therefore mimics surface topography, and regional groundwater flow is from higher lying ground towards lower lying valleys, where it accumulates in the alluvial deposits and contributes to river baseflow. Note that local flow patterns may differ due to the fractured nature of the aquifers in the area.

A 10 m groundwater contour map was developed by Mr Frans Wiegman from Golder Associates and is presented in Figure 3. The piezometric map shows a regional groundwater flow direction towards the west. Groundwater piezometric contours immediately south and west of the Danielskuil dyke (shown in Figure 3) are typical of dolomite aquifers with low hydraulic gradients due to high aquifer transmissivities within dolomitic compartments, bounded by dykes with major steps in piezometric levels, where levels on the one side are substantially lower. Piezometric levels north and northwest of the model domain show steeper gradients, indicating lower transmissivities in the BIF hard rock aquifer.

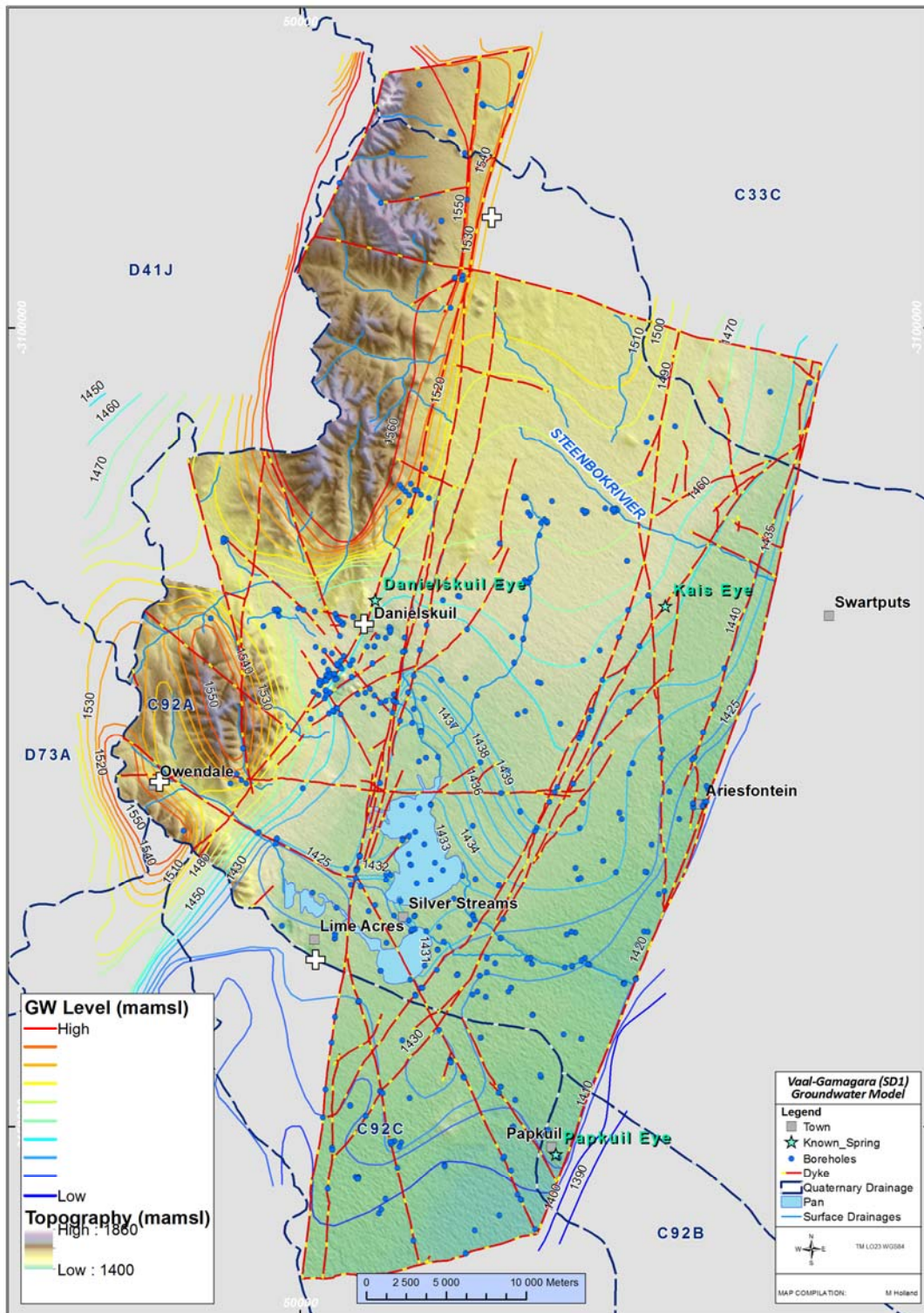


Figure 3: Groundwater piezometric map and topographical setting.

3. MODEL CONSTRUCTION

3.1. COMPUTER CODE

The software code chosen for the numerical finite-element modelling work was the 3D groundwater flow model SPRING, developed by the delta h Ingenieurgesellschaft mbH, Germany (König, 2011). The program was first published in 1970, and since then has undergone a number of revisions. SPRING is widely accepted by environmental scientists and associated professionals. SPRING uses the finite-element approximation to solve the groundwater flow equation. This means that the model area or domain is represented by a number of nodes and elements. Hydraulic properties are assigned to these nodes and elements and an equation is developed for each node, based on the surrounding nodes. A series of iterations are then run to solve the resulting matrix problem utilising a pre-conditioning conjugate gradient (PCG) matrix solver for the current model. The model is said to have “converged” when errors reduce to within an acceptable range. SPRING is able to simulate steady and non-steady flow, in aquifers of irregular dimensions. SPRING solves the stationary flow equation independent of the density for variable saturated media as a function of the pressure according to:

$$-\nabla(K_{ij}\nabla h) = -\nabla\left(K_{perm}\frac{\rho g}{\mu}\nabla h\right) = q = -\nabla\left[\frac{K_{perm} \cdot k_{rel}}{\mu}(\rho g\nabla z + \nabla p)\right]$$

$$\nabla \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$$

q	Darcy flow
K_{ij}	Hydraulic conductivity tensor
ρg	Density · gravity
K_{perm}	Permeability
μ	Dynamic viscosity
k_{rel}	Relative permeability
p	Pressure

The relative hydraulic conductivity is hereby calculated as a function of water saturation, which in turn is a function of the saturation:

$$k_{rel}(S_r) = (S_e)^l \left[1 - \left(1 - (S_e)^{\frac{1}{m}} \right)^m \right]^2$$

$$S_e = \frac{S_r(p) - S_{res}}{S_s - S_{res}} = \left[1 + \left(\frac{p_c}{p_e} \right)^n \right]^{\frac{1-n}{n}}$$

$S_r(p)$	Relative saturation dependent on pressure
S_e	Effective saturation
l	Unknown parameter, determined by van Genuchten to 0.5
m	equal to $1 - (1/n)$
n	Pore size index
S_{res}	Residual saturation
S_s	Maximum saturation
p_c	Capillary pressure
p_e	Water entry pressure

Solving these equations for the relative saturation as a function of the capillary pressure $S_r(p_c)$ results in the capillary pressure- saturation function according to the Van Genuchten (1980) model as used in SPRING:

$$S_r(p_c) = S_{res} + (S_s - S_{res}) \cdot \left[1 + \left(\frac{p_c}{p_e} \right)^n \right]^{\frac{1-n}{n}}$$

The water entry pressure is a soil specific parameter and defined as the inverse of $a = 1/p_e$ in the saturation parameters.

The density independent, instationary flow equation for variable saturated media as a function of the capillary pressure is given as follows:

$$\rho \left(S_r(p_c) S_{sp} + \theta \frac{\partial S_r(p_c)}{\partial p} \right) \frac{\partial p}{\partial t} + \theta S_r(p_c) \frac{\partial \rho}{\partial t} - \nabla \left[\rho \frac{K_{perm} k_{rel}}{\mu} (\nabla p + \rho g \nabla z) \right] = q$$

The specific pressure dependent storage coefficient S_{sp} is hereby given as

$$S_{sp} = \alpha(1 - \theta) + \beta\theta$$

- α Compressibility of porous media matrix
- β Compressibility of fluid (water)
- θ Aquifer porosity

3.2. MODEL DOMAIN

The model domain boundaries were established during the conceptualisation phase by Mr Frans Wiegman and adapted accordingly by Delta-H. The model boundaries were chosen along mapped dykes, often coinciding with the quaternary catchment (C92A) boundaries, so as to ensure a dependable water balance for the model with recharge being the main driver of groundwater flow. A number of head dependant boundary conditions were assigned mainly along the eastern and southern edge of the model domain representing potential groundwater outflow towards adjacent aquifer systems (Figure 4).

The total model domain covers an area of 1 826 km² and was spatially discretised into 111 512 nodes on 5 node layers, which make up 4 element layers with 121 468 elements (triangles and quadrangles) per layer, to account for the various hydrogeological units underlying the proposed well fields.

The horizontal element size (side length) varies from a minimum of 30 to 50 m (average) along surface drainages and mapped dykes and faults (as provided by Golder Associates), to a maximum side length of 200 m further away from the area of interest. The chosen model discretisation allows a sufficiently accurate representation of discrete physical features (dykes, fault zones and drainages) in a regional groundwater flow model, employed to ensure a justifiable water balance and natural upstream boundaries of the flow system for the area of interest.

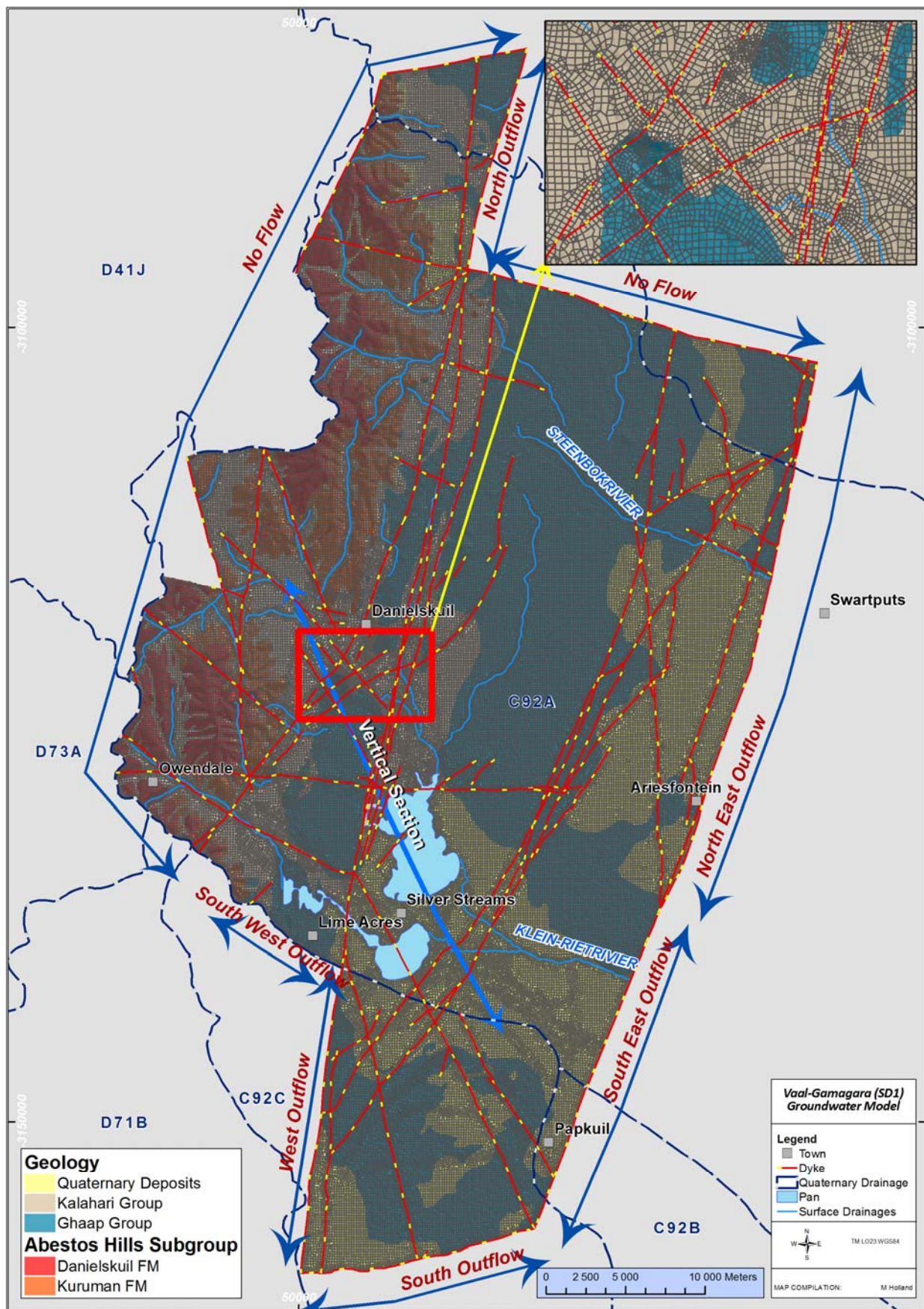


Figure 4: Generated mesh for the SD1 model domain (also showing cross-section references).

3.3. MODEL LAYERS

The finite-element model was set-up as a three-dimensional four element layer groundwater flow model. The vertical model discretisation respectively model layer coincide with the conceptual hydrogeological model provided by the client.

The upper layer (split into two model layers to increase the accuracy of the unsaturated flow calculations) represent the highly weathered- and karst aquifer to a depth of 4 m below the interpolated groundwater level. The third layer represents the highly karstified hydrogeological unit to a depth of 15 m below the interpolated groundwater level. The bottom elevation of the groundwater flow system was set at approximately 90 m below the current groundwater level, resulting in a model thickness ranging from 92 to 370 m. The layer arrangement is summarised in Table 1 and shown in a cross-section in Figure 5. The vertical section chosen along the Idwala Mine Quarry and The Great Pan (north of Silver Streams) (see Figure 4) shows the vertical discretisation of the model domain.

Table 1: Layer arrangement for the SD1 groundwater model.

Node layer	Element layer	Map colour	Aquifer feature	Data used for interpolation
1	I, top		Surface elevation	SRTM 90 m Digital Elevation Model (DEM)
2	I, bottom		Weathered- and Karst Aquifer	Divide Layer 1 into 2 (Equal proportion)
3	II, bottom		Weathered- and Karst Aquifer	Fixed offset of 4 m from interpolated water level
4	III, bottom		Karst Aquifer	Fixed offset of 15 m from interpolated water level
5	IV, bottom		Karst Aquifer	90 m below Water Table

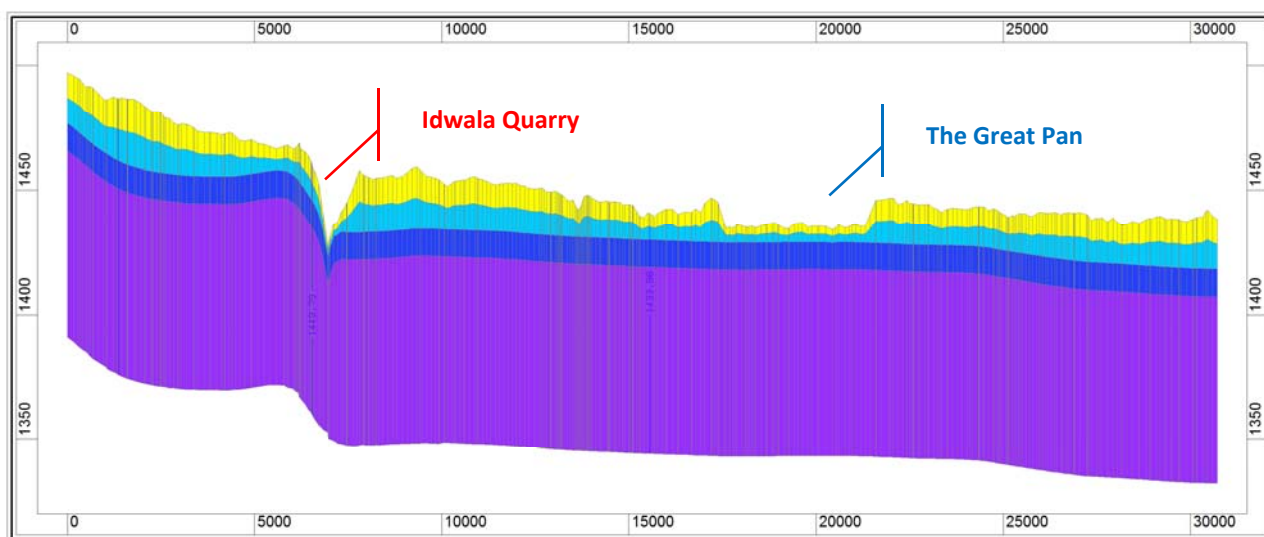


Figure 5: Example of the vertical grid layout (vertically exaggerated).

3.4. HYDRAULIC PARAMETER

Over 55 transmissivity values were collated from either historical data or as part of the (drilling) exploration programme for the proposed well fields. The hydraulic conductivity ranges shown in Table 2 were used as initial parameters for the model calibration. The initial model calibration used the gradient method within the SPRING software package, whereby the permeability of the elements are iteratively varied until a good fit of the piezometric contours respectively their gradients is achieved, rather than fitting a single point value or head. The gradients of the initial state were based on the piezometric head contours discussed earlier (section 2.3).

The (geometric) mean transmissivity obtained from pumping tests analysis is considered the most appropriate estimate of the average effective conductivities for the region. Over the entire area (or model domain) the geometric mean transmissivity is 268 m²/d (Table 2). The lower permeability dykes was specified from 1e-7 to 1e-8 m/s for the initial model runs.

Table 2: Transmissivity and hydraulic conductivity ranges for the SD1 region.

Stat.	T-Value (m ² /d)	Hydraulic Conductivity	
		(m/d)	(m/s)
Arithmetic mean	1029	11.4	1.3E-4
Median	480	5.3	6.2E-5
Geometric mean	268	3.0	3.5E-05

In accordance with literature values, vertical hydraulic conductivities were for all layers consistently set at 40% of the horizontal hydraulic conductivities. This approach avoids the introduction of another unknown set of model respectively calibration parameter, by tying the vertical and horizontal hydraulic conductivities. The calculation of the unsaturated hydraulic conductivity values uses the Van Genuchten model, with typical parameters for the weathered zone.

During the predictive (transient) modelling runs, the groundwater system is dynamic, with changes in groundwater storage occurring as a result of the assigned variability of rainfall respectively recharge and abstraction rates. The storativity values shown in Table 3 are based on the 18 pumping test analyses (of observation boreholes) during constant rate discharge tests of the SD1 well field. The results indicate both unconfined and confined conditions. The storativity of a confined aquifer, which varies with specific storage and aquifer thickness, typically ranges from 5E-05 to 5E-03 (Todd, 1980); whereas in unconfined aquifers storativity or specific yield ranges from 0.1 to 0.3 (Lohman, 1972). Specific storage values of 1E-03 to 0.3 were used for the dolomite aquifers, representative of semi-confined karst aquifer conditions.

Table 3: Storativity values determined for SD 1 well fields.

Parameters	Storativity Values [S]
Minimum	2.3E-8
Maximum	0.35
Mean	0.05
Median	0.0059

3.5. SOURCES AND SINKS

3.5.1. Recharge

The spatial distribution of the recharge rates delineated by Golder Associates and used in the model together with the location of rainfall station is shown in Figure 6.

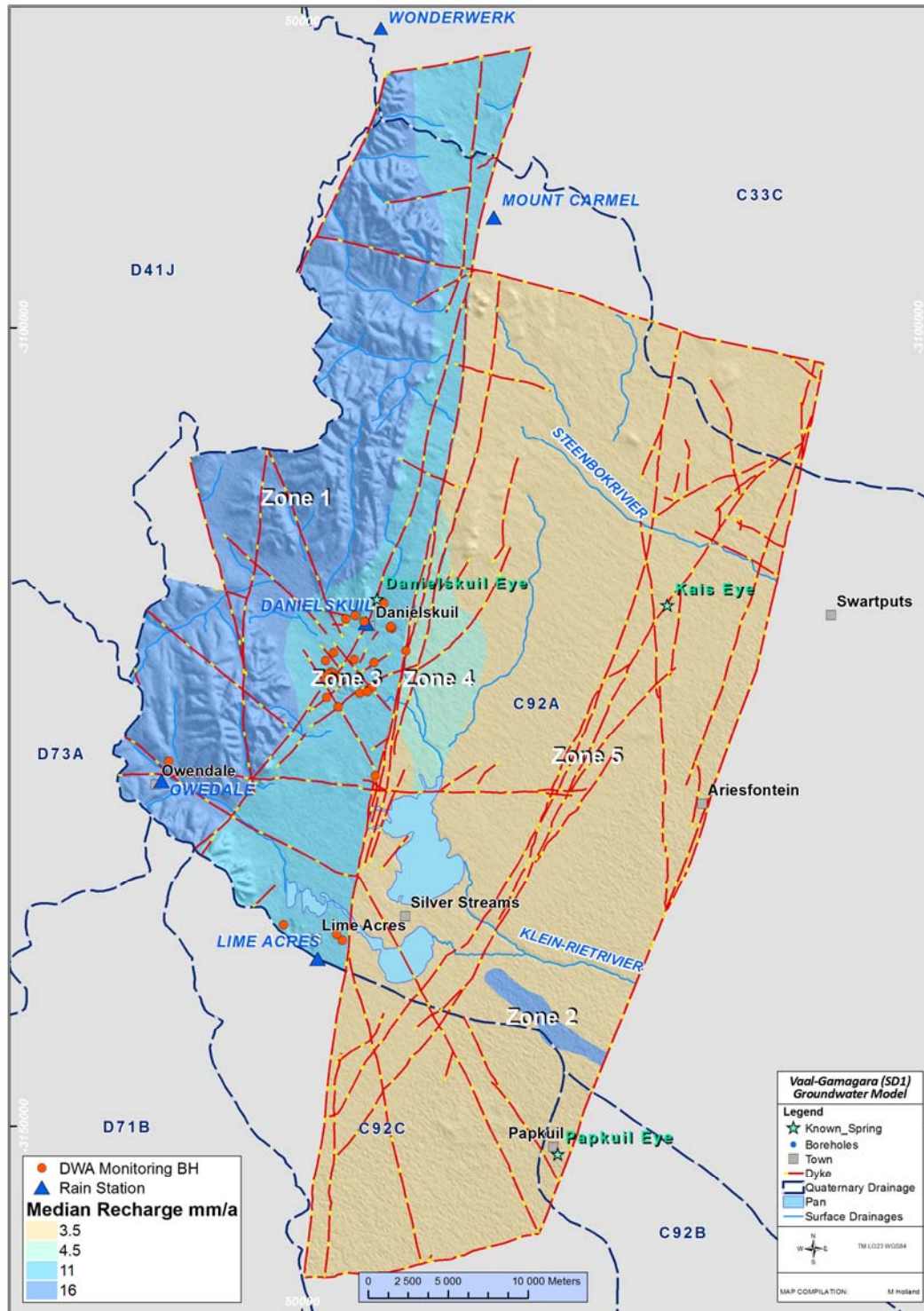


Figure 6: Recharge rates (and zones) assigned in the SD1 groundwater model.

Groundwater enters the model domains as direct recharge from rainfall. It was implied that certain areas may have greater recharge potential and may thus contribute a larger proportion of recharge towards the aquifer systems respectively. Based on the conceptual understanding of the SD1 groundwater system, the median annual recharge values range between 3.5 and 16 mm (Figure 6).

3.5.2. Time dependent recharge

The spatial distribution of existing groundwater monitoring boreholes is shown in Figure 6. Available groundwater monitoring data is mainly located within recharge zone 1, 3 and 4, and absent in recharge zone 2 and 5. It must also be noted that not all monitoring boreholes have complete records of water levels, or represent in some cases water levels during pumping conditions and not static (rest) water levels.

Nevertheless, monitoring data show a good relationship between the Cumulative Rainfall Departures (CRD) from the mean rainfall (for the Danielskuil rainfall station) and observed water level fluctuations in the dolomitic aquifer, which indicates dynamic recharge (Figure 7). Since the direct cause/effect relationship between the CRD and water levels was observed, an empirical relationship between rainfall and recharge events can be assumed. Based on earlier modelling studies conducted on dolomitic terrain, an exponential relationship between recharge and rainfall produced acceptable results.¹ The resulting recharge (mm/month) was derived as a fraction of rainfall based on the following formula:

Recharge Fraction = $0.05e(0.01 * \text{Rainfall})$.

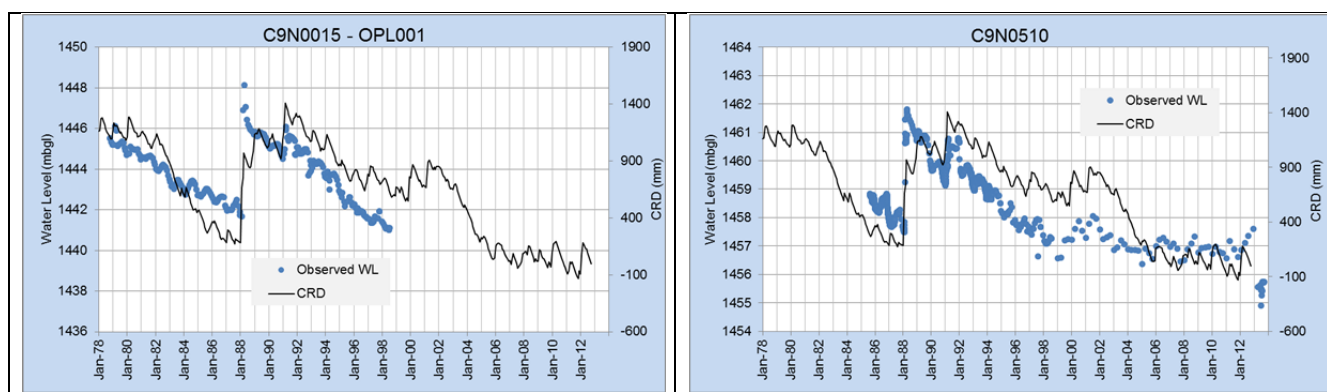


Figure 7: Groundwater level versus the Cumulative Rainfall Departure.

3.5.3. Groundwater abstraction

Both steady state and transient borehole abstraction from the model domain was simulated using the withdrawal well boundary condition. Outflow rates were assigned to single nodes (at the appropriate elevation) within the model mesh. For fully penetrating wells, equal heads were prescribed for all applicable well nodes and the inflows for each node automatically calculated by the software. The annual abstraction rate applied to the steady state model amounts to 231,797 m³/month or 2,781,564 m³/annum.

¹ Personal Communication – Mr. Frans Wiegman (Golder Associates) and Dr. Hugo Van Rensburg (Aquisim Consulting).

3.5.4. River courses and springs

Groundwater within the study area was assumed to originate as spatially distributed rainfall recharge within the model domain (see chapter 3.5.1). It is thought that a portion of the groundwater recharge occurring within the model domain discharges internally to surface drainage systems via springs or as discharge to the river drainage systems (baseflow). The interaction between groundwater and surface water courses was simulated under the assumption of continuous gaining river systems (i.e. groundwater is only allowed to discharge into them and not vice versa). These drainages were therefore described within the model using SPRING's 'river package', with no exfiltration of surface water allowed. The stage of each river node was carefully aligned with the height of the Digital Elevation Model (DEM) at that point and an incision the river bottom of 2 m below topography assumed. A river bed conductance of $1\text{E-}7$ m/s was assumed. Known springs (see Figure 3) within the SD1 area (see Photo 1) were incorporated as leakage boundary conditions at the specific node of the spring location.



Photo 1: Danielskuil Eye (Photo taken by Danie Brink – Golder Associates).

3.5.5. Mine Quarry (Open Cast)

The Idwala open cast mine working (pit) was integrated into the model domain for the predictive simulations by updating the digital elevation model for the pit area and assigning a free seepage boundary to the pit area. It is assumed that any groundwater entering the pit is removed (pumped out) and that the pit bottom represents therefore the lowest drainage elevation. In other words, groundwater is allowed to seep freely into the pit with a subsequent development of a cone of dewatering. It must be noted that the computation of the free groundwater table and pit inflows consider partially saturated flow conditions using the van Genuchten equation to calculate the relative permeability as a function of the capillary pressure, saturation, residual saturation and entry pressure.

3.6. SELECTION OF CALIBRATION TARGETS AND GOALS

3.6.1. Steady state calibration targets

Once a reasonable fit of the piezometric contours respectively their gradients was established using the gradient method within the SPRING software package, the measured groundwater levels (in metres above mean sea level) observed in 373 boreholes were used as calibration targets. The regional water level measurements spread over a number of decades and represent therefore by no means a single snapshot of water levels taken under the same climatic conditions and land uses or average conditions. The project team biased therefore the steady state calibration towards a reasonable fit of the most recent water levels respectively abstraction and recharge conditions. The three available spring outflows together with the Idwala Pit inflows were considered as secondary targets in the calibration process.

Since the modelled groundwater levels are directly related to the assigned recharge rates and hydraulic conductivities, an independent estimate of one or the other parameter is required to arrive at a potentially unique solution of the model calibration. The estimated recharge rates were therefore considered fixed for the steady state calibration and only hydraulic conductivities considered variable, i.e. adjusted within reasonable boundaries (Table 2) to represent the observed flow system.

3.6.2. Transient calibration targets

In order to simulate the temporal responses of the aquifers to variable rainfall recharge and external stresses (abstractions), a transient calibration of the steady-state model is required. Although transient calibration introduces another uncertain fitting parameter, namely the storage coefficient S (as a sum of specific storativity and yield for unconfined aquifers), it partially eliminates the non-uniqueness of the steady-state calibration parameters and provides additional insight into the appropriateness of the conceptual model.

Transient simulations require the definition of stress periods, during which boundary conditions remain constant, and time steps, for which model calculations are made. Since the frequency of the rainfall measurements were provided on a monthly basis the water balance of the model was calculated on a monthly time-step. Stress periods assigned in the present model can be divided into two components:

1. The first component covers the transient calibration phase from 1978 to 2012 and entailed 421 (months) stress periods with variable monthly recharge rates.
2. The second component entails stress periods assigned for the predictive model runs considering various aquifer management scenarios for the period 2013 to 2030 (205 stress periods).

The model was further optimised by calibrating the simulated heads to observed pumping test drawdown data for 10 SD1 production boreholes. The pumping tests ranged from 24 to 72 hours and the transient model comprised of 73 one-hour time steps. A summary of the calibration targets is shown in Table 4. The pumping tests however, do not represent the entire the model domain and was limited to the SD1 well field region.

Table 4: Boreholes (with pumping test data) used as transient calibration targets.

BH ID	Model Node	L/S	m ³ /hour	Time (Minutes)
SD1-08	69	30	108	1440
SD1-16	77	20	72	2880
SD1-17M	163	30	108	4320
SD1-20	82	30	108	1440
SD1-25	87	30	108	4320
SD1-27	89	30	108	2880
SD1-32M	95	30	108	4320
SD1-35M	101	30	108	4320
SD1-40	105	10	36	4320
SD1-44	109	30	108	4320

3.7. NUMERICAL PARAMETERS

SPRING uses an efficient preconditioned conjugate gradient (PCG) solver for the iterative solution of the flow equation. The closure criterion for the solver, i.e. the convergence limit of the iteration process was set at a residual below 1e-06. The Picard iteration, used for the iterative computation of the relative permeability for each element as a function of the relative saturation respectively capillary pressure, used a damping factor of 0.5 and was limited to 5 iterations. The relative difference between the calculated capillary pressures of a node after 5 iterations was generally below an acceptable 0.1 m.

3.8. INITIAL CONDITIONS

The initial conditions specified in numerical model were as follows:

- Starting heads were interpolated from the piezometric contour map described in section 2.3.
- The gradient method calculation based on the piezometric data (initial heads) was used to establish initial hydraulic conductivities over the model domain. The model run was initiated with hydraulic conductivities of 1E-06 m/s, a minimum of 1E-09 m/s and a maximum of 1E-04 m/s.
- Vertical hydraulic conductivities were set at 40% of the horizontal conductivities.

4. MODEL CALIBRATION

4.1. STEADY-STATE CALIBRATION

SPRING uses the gradient method for the calibration of the permeabilities (synonymously used to describe hydraulic conductivities) of the elements in the groundwater flow model. Since the calibration is undertaken for an assumed steady state scenario, it is necessary to use initial conditions that are as close as possible to the steady state conditions of the real system. The groundwater gradients of this initial state must conform to the overall flow direction or the resulting (calibrated) permeabilities may be incorrect. The piezometric map shown in Figure 3 is an assumed steady-state map of groundwater elevations (equipotential heads) and was subsequently used for the steady-state calibration. Due to the size of the model domain and the time required to do a model run, the initial spatial calibration of the permeabilities was done with a 2D model, which was subsequently extended to the full 3D model.

The gradient method uses spatially distributed data (heads respectively gradients) for the calibration of permeabilities and generally achieves a very good description of the spatial groundwater flow directions and the observed heads. Once a reasonable fit of the simulated and the observed water levels was found, the single model layer was subdivided according to the conceptual model (see chapter 3.3) and the hydraulic conductivities of the 3D model manually adjusted to more accurately represent the measured heads and actual hydrogeological conditions (e.g. permeabilities across dykes and highly transmissive zones). The spatial distribution of the calibrated conductivity values for layer I is shown in Figure 8 and the values for all model layers summarised in Table 5.

Table 5: Calibrated hydraulic conductivity ranges for the SD1 groundwater model.

Layer	Aquifer	Hydraulic conductivity [m/s]	
		Min	max
I-IV	Dyke (Barriers to Flow)	1E-9	1E-7
I, II and III	Weathered- and Karst Aquifers	1E-6	4E-4
	BIF	1E-7	5E-6
IV	Deep Karst Aquifer	5e-7	1e-5

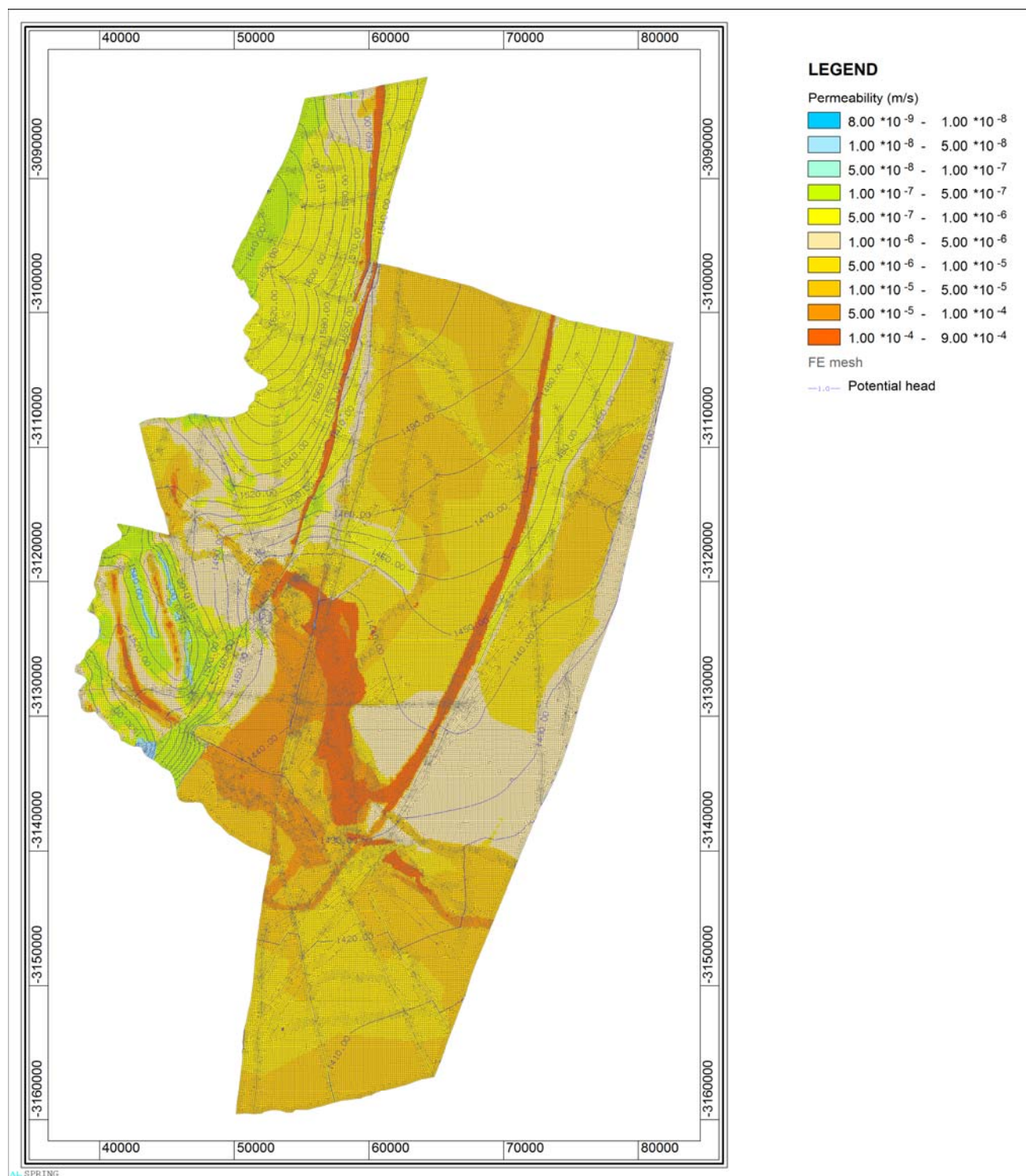


Figure 8: Distribution of permeabilities (layer 1 to 3) together with steady state heads (10 m contour interval).

4.2. QUALITATIVE/QUANTITATIVE ANALYSIS

The original model was run with the initial conditions described above and the permeabilities adjusted using sensible boundaries (Table 2) until a best fit between initial and computed potential heads was achieved (Figure 9).

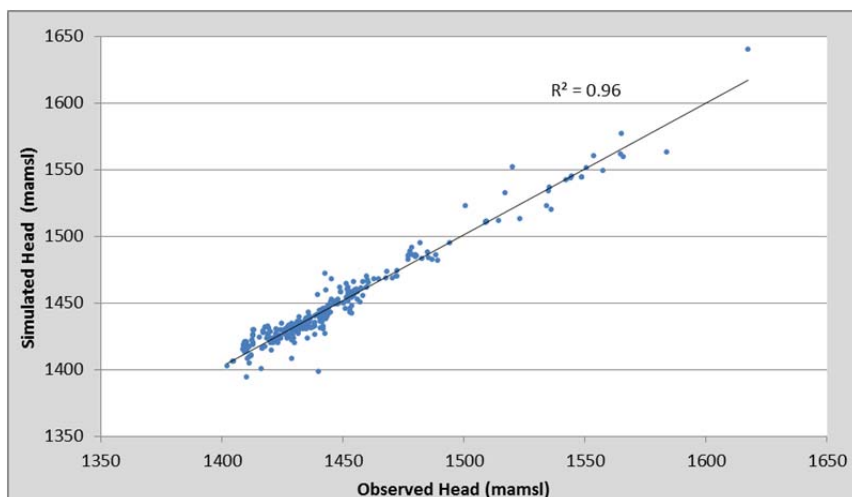


Figure 9: Steady state calibration of the SD1 groundwater model.

A very good statistical correlation coefficient ($R^2=0.96$) between modelled and observed values of essentially 96% with no obvious bias of modelled heads (Figure 9) was achieved for the steady-state calibration. It must be noted that a 96% correlation does not mean that each measured head is exactly replicated by the model, but that the sum of (normalised) squared differences between observed and simulated heads is just below unity. The corresponding root mean square error (RMSE), essentially the variance of the simulated heads if the observed heads are used instead of the average for the calculation, of 6.5 is considered more than acceptable. The RMSE for the 50 SD1 well field boreholes alone is with 2.1 considered excellent. Expectedly, the model is able to simulate the observed potential heads for the well field very well as is shown in Figure 10.

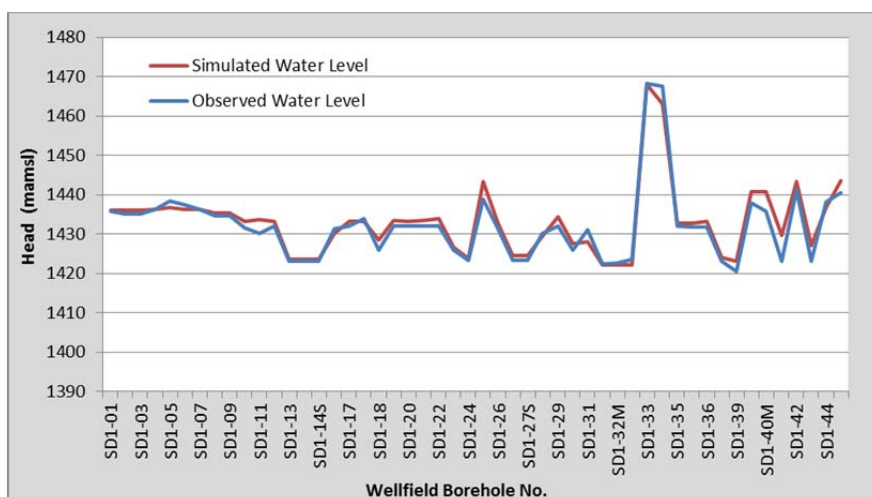


Figure 10: Line plot of simulated versus the observed groundwater levels for the SD1 well field.

4.3. TRANSIENT CALIBRATION

For the transient calibration the available long term water level monitoring and 10 (SD1) pumping test datasets were used as calibration targets.

4.3.1. Long term trend (1978 to 2012)

The main aim of the calibration was to match the “signature” or behaviour of temporal water table fluctuations observed, rather than the actual head itself. Figure 11 shows a comparison of simulated vs. observed heads for a number of representative boreholes.

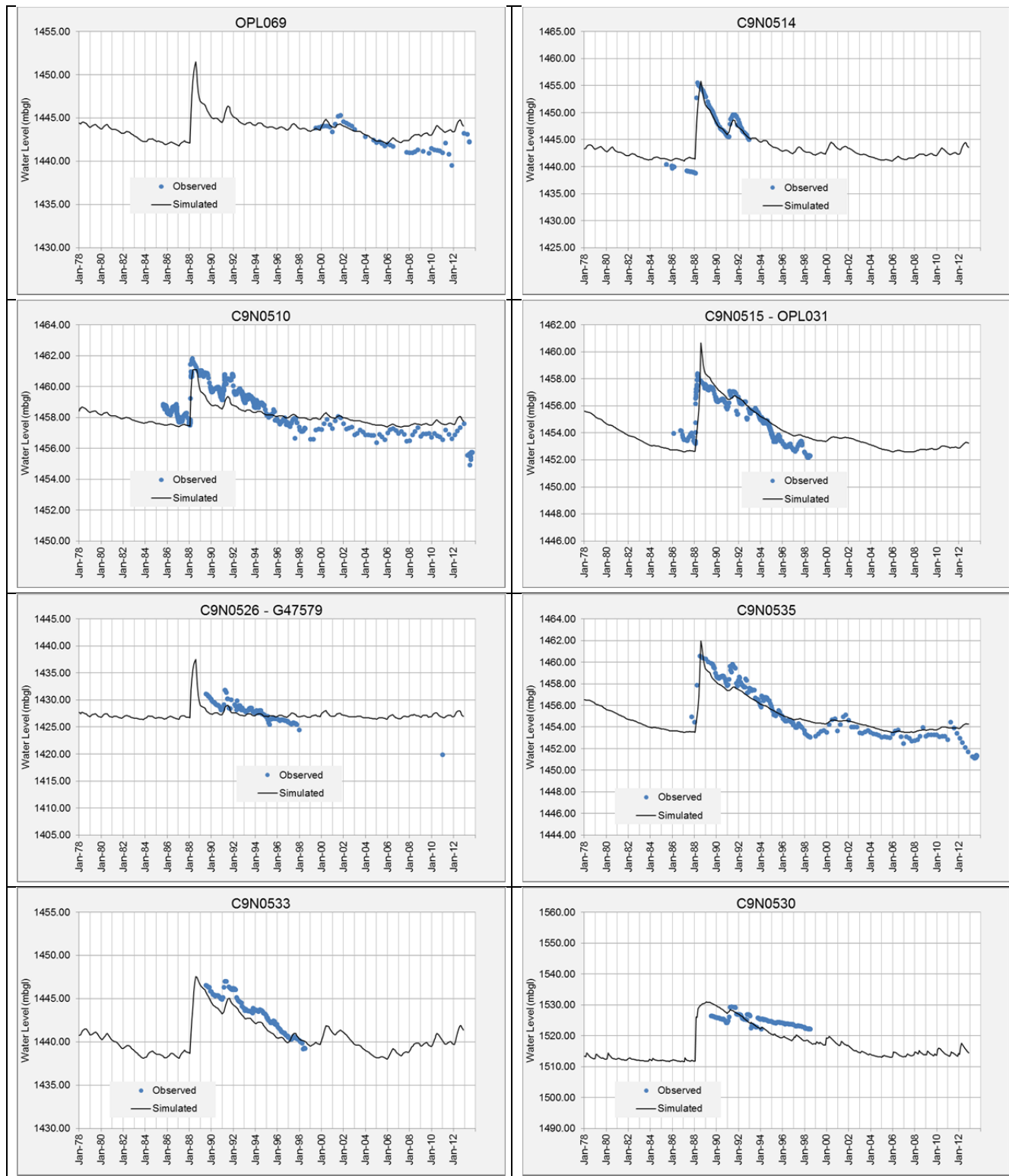
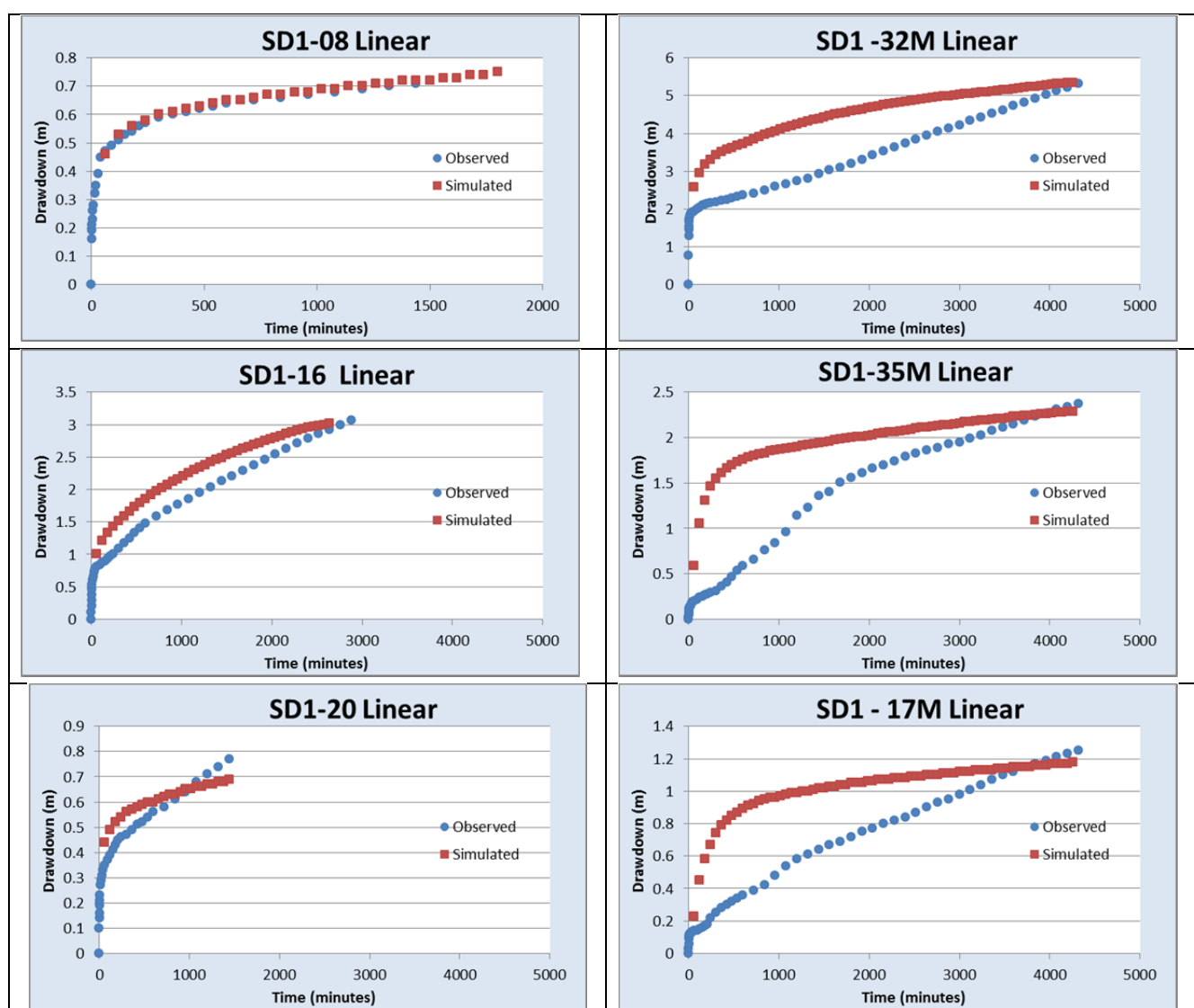


Figure 11: Simulated versus observed groundwater levels.

Based on the results, it is evident that in most cases the “signature” of the temporal water level fluctuations is sufficiently well represented by the model. The “off-set” between observed and simulated heads for some boreholes appears to be a result of the assigned steady state starting water levels, which reflect average and not actual historical water levels at a given point in time. In all cases, this “off-set” is acceptable (within 2 meters) and within the seasonal range of water level fluctuations.

4.3.2. Pumping Test (Time drawdown calibration) (24 to 72 hours)

The transient calibration of pumping test datasets refines and verifies the steady-state calibration by matching transient hydraulic-head trends which reflect the stresses of pumping from the production boreholes. The transient model calibration was used to optimize the spatial variability of storage coefficients.



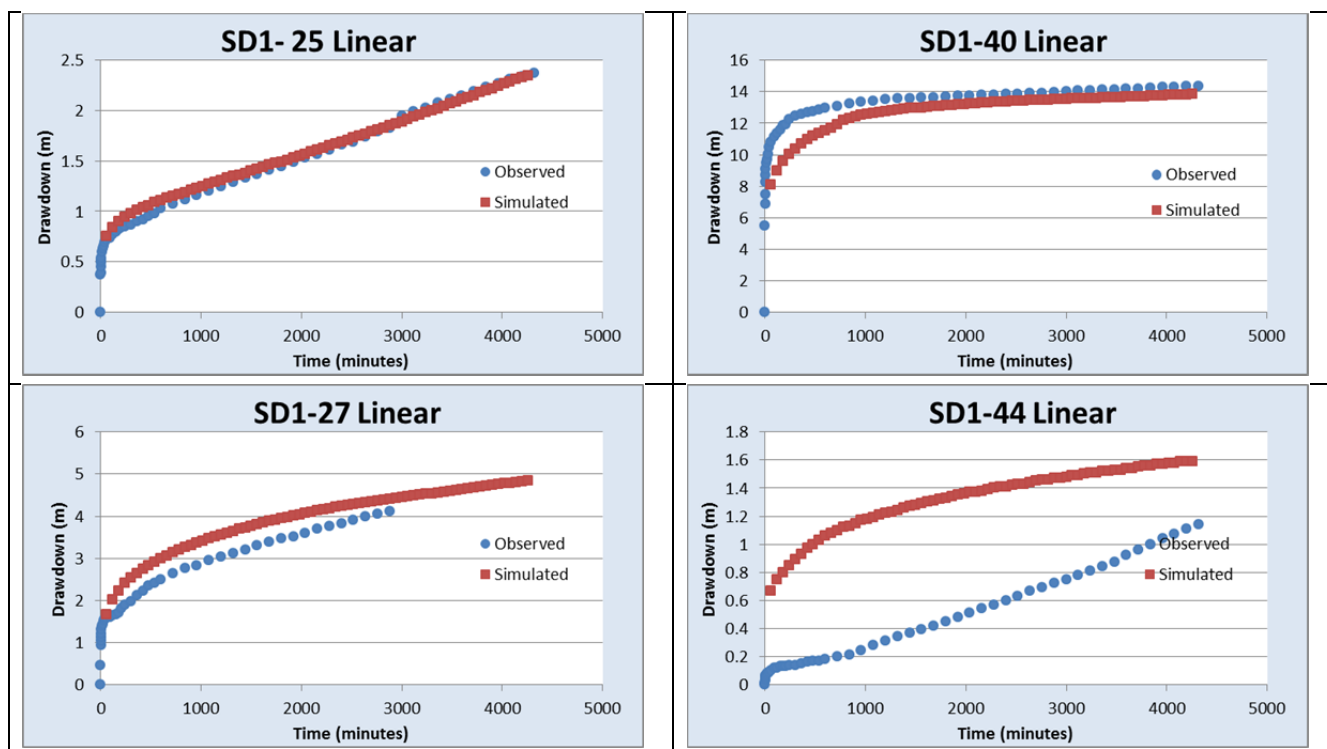


Figure 12: Transient model calibration using normalized (to initial static) drawdown.

An acceptable fit is observed for most pumping test boreholes. However, it is evident that in some cases the drawdown behaviour cannot be accurately represented due to the heterogeneity of fracture distributions and subsequent hydraulic discontinuities proximal to the pumping well. When interpreting pumping test results, it is essential to realise that they access only limited volumes of the aquifer for the duration of the test. Extrapolation of results from pumping tests must therefore be undertaken cautiously, with an awareness of the limitations of the data. Incidentally, the rate at which the cone of depression propagates in an aquifer (similar to a surface wave in a lake) does not depend on the pumping rate, but on the aquifer hydraulic diffusivity (the ratio of the aquifer transmissivity and storage coefficient)

4.4. SENSITIVITY ANALYSIS (STEADY STATE)

The purpose of a sensitivity analysis, i.e. the systematic variation of the model parameter within their upper and lower bounds, is to identify the model response to the uncertainty associated with each of the input parameter. The range of simulated model outputs shows the uncertainty associated with each parameter as well as the potential non-uniqueness of the calibration if the model proves to be insensitive towards a calibrated parameter, which should then be determined independently. Parameters, which were investigated in terms of their model sensitivity, along with their upper and lower boundaries are shown in Table 6.

Table 6: Parameter boundaries used in the sensitivity analysis.

Parameter and Region	Low Variable (factor)	Calibrated	High Variable (factor)
Conductivity	0.5	1	1.5
Recharge	0.5	1	1.5

A normalized sensitivity index S was computed utilizing the 372 observation wells according to:

$$S = \frac{1}{n} \sum_n \frac{|dh_n|}{dp} \frac{p}{p}$$

Where

$|dh|$ is the difference of the observed variable (drawdown) between the parameter varied case and the base case, dp/p is the relative change of the varied parameter, and n corresponds to the number of selected observation points.

The resulting sensitive analysis is presented in Figure 13. Negative values were ascribed if parameter values were lowered and vice versa, while the magnitude of S is a measure of the sensitivity of the model to a change in the corresponding parameter p .

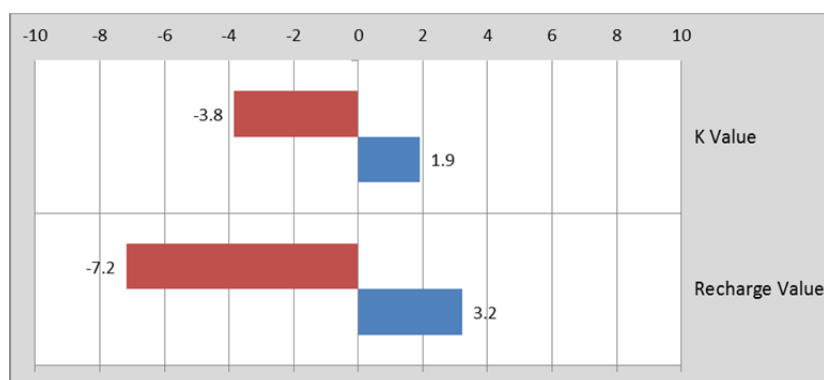


Figure 13: Sensitivity indices for tested parameter ranges.

It is obvious from the sensitivity indices (Figure 13) that the simulated water levels are most sensitive to

1. a reduction in recharge, compared to
2. lower hydraulic conductivities and higher recharge rates, while
3. an increase in conductivities is the least sensitive parameter.

Based on the outcome of the simplified sensitivity study, it can be deduced that the regional recharge rates should be determined to a high level of confidence. Accurate derivation of these values will obviously increase the level of confidence in model outputs.

5. PREDICTIVE SIMULATIONS

5.1. WATER BALANCE

A summary of the steady state water balance is provided in Table 7. The steady-state water balance (Table 7) shows that the vast majority of recharge (which is the only model inflow) contributes to baseflow in drainages (including evapotranspiration losses along these drainages and pans) and spring discharges within the model domain, with only around 26 % of the inflow (recharge) reporting to the head dependent outflow boundaries, i.e. towards downstream catchments. Total (steady-state) groundwater abstractions consume for the steady-state scenario around 20% of the total recharge for the area. The Idwala pit inflows was estimated at 26,311 m³/month compared to an alleged inflow of approximately 22,000 m³/month.

Table 7: Regional steady-state water balance.

Regional Water Balance		
Inflow	m ³ /month	m ³ /annum
Recharge	1 176 273	14 115 274
Outflow	m ³ /month	m ³ /annum
Spring Discharge	-33 523	-402 276
Boreholes Abstraction	-231 797	-2 781 564
Contribution to Drainages, pans and potential evapotranspiration	-575 713	-6 908 554
Outflow Boundary	-308 929	-3 707 148
Idwala Pit Inflows	-26 311	-315 732
Total Outflow	-1 176 273	-14 115 274

5.2. APPLIED RAINFALL VARIABILITY (2013 TO 2030)

The calibrated transient model was subsequently used to simulate the impact of proposed abstractions from the SD1 well field on the water levels and water balance of the regional aquifer system. The predictive scenario was simulated based on historically observed rainfall variability. The rainfall/recharge data from 1996 to 2012, which is regarded to be a conservative approach, was used to simulate the rainfall recharge in the predictive scenario (Figure 14).

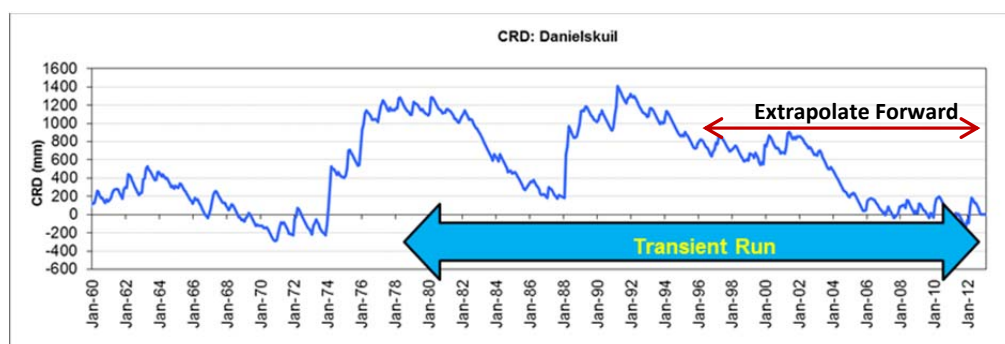


Figure 14: CRD curve for the Danielskuil rainfall station showing the extrapolated scenario (red arrow) interval used for the predictive simulations.

5.4. APPLIED ABSTRACTION SCENARIOS (2013 TO 2030)

The forward simulations of the proposed SD1 Well field considered four abstraction scenarios, namely:

- Scenario 0 – Base or reference case with no abstractions, i.e. the well field project no-go option.
- Scenario 1 – 22 SD1 and 3 Danielskuil production boreholes
 - o Upper limit abstraction with a combined yield of 724,890 m³/month (8.7 Mm³/annum) for the SD1 production boreholes and 39,420 m³/month (0.47 Mm³/annum) for the designated Danielskuil boreholes.
- Scenario 2a – 15 SD1 and 3 Danielskuil production boreholes
 - o Optimised long term abstractions with a combined yield of 444,132 m³/month (5.3 Mm³/annum) for the SD1 production boreholes and 19,710 m³/month (0.24 Mm³/annum) for the designated Danielskuil boreholes.
- Scenario 2b – 15 long term SD1 boreholes and 7 interim SD1 boreholes only initiated (into production) from 2015 to 2017 and again from 2024 to 2026 together with the 3 Danielskuil production boreholes
 - o Optimised long- and short term abstractions with a combined yield of 553,632 m³/month (6.6 Mm³/annum) for the SD1 production boreholes and 19,710 m³/month (0.24 Mm³/annum) for the designated Danielskuil boreholes.

The various abstraction scenarios are shown in Table 8, while the position of the SD1 well fields and associated (upper limit Scenario 1) abstraction rates is shown spatially in Figure 15.

Table 8: Abstraction rates for the forward Scenario's 1, 2a and 2b.

Well field No.	BH no.	Scenario 1 m ³ /month	Scenario 2a m ³ /month	Scenario 2b m ³ /month
Danielskuil	SD1-33	6 570	6 570	6 570
	SD1-34	6 570	6 570	6 570
	SD1-45	26 280	6 570	6 570
Well field No 1	SD1-04	32 850	21 900	21 900
	SD1-08	54 750	43 800	43 800
	SD1-09	32 850	0	21 900
	SD1-25	26 280	0	19 710
	SD1-44	65 700	52 560	52 560
Well field No 2	SD1-10	32 850	32 850	32 850
	SD1-11	32 850	21 900	21 900
	SD1-16	21 900	10 512	10 512
	SD1-17	26 280	19 710	19 710
	SD1-19	26 280	0	19 710
	SD1-20	52 560	52 560	52 560
	SD1-21	26 280	26 280	26 280
	SD1-22	10 950	0	6 570
	SD1-26	21 900	0	21 900
Well field No 3	SD1-35	65 700	52 560	52 560
	SD1-24	52 560	32 850	32 850
	SD1-27	32 850	21 900	21 900
	SD1-32	52 560	32 850	32 850
Well field No 4	SD1-43	21 900	0	10 950
	SD1-40	10 950	0	8 760
	SD1-41	13 140	10 950	10 950
	SD1-42	10 950	10 950	10 950
Total m³/month		764 310	463 842	573 342
Total m³/annum		9 171 720	5 566 104	6 880 104

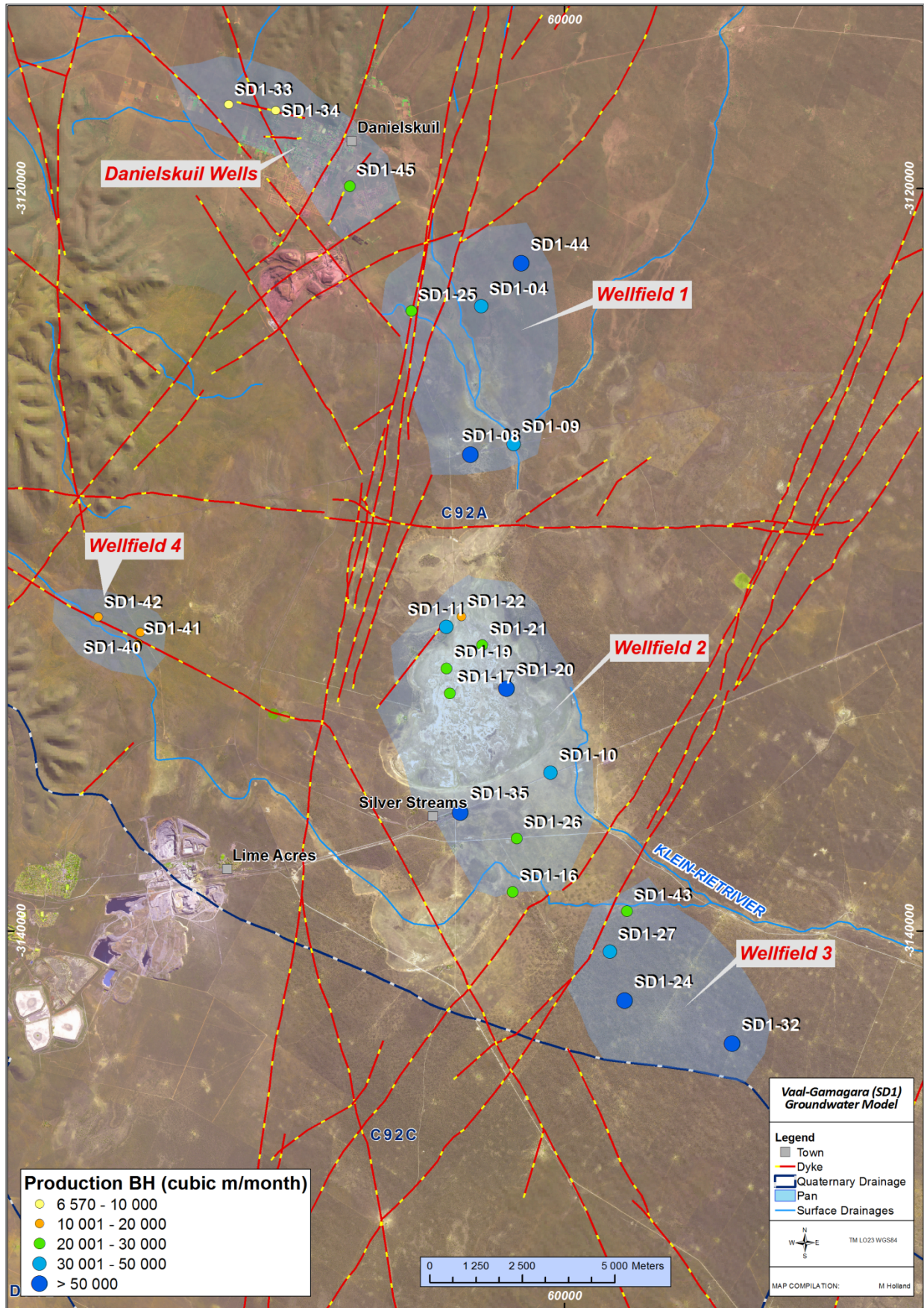


Figure 15: Locality of SD1 well fields (Scenario 1).

5.5. IMPACTS ON THE WATER LEVELS ASSOCIATED WITH THE SD1 WELL FIELD

The simulated impacts of the groundwater abstraction from the SD1 well field on the regional groundwater levels are shown as contour maps of drawdown by comparing the water levels simulated for the last stress period of the base case (no well field abstractions) (2030) simulation against the lowered water levels due to abstraction from the SD1 well field (2030).

No drawdown values below 2 meters are visualised to account for the inaccuracy in the model calibration, which is within the expected seasonal variability of water table elevations. It is likely that any drawdown below 2 meters is within the range of natural water table fluctuations and therefore any potentially affected groundwater dependent ecosystem therefore adapted to it. Similarly, potential groundwater users are unlikely to recognise such drawdown as borehole yields are typically not significantly impacted by such seasonal fluctuations.

Scenario 1 can be considered as a worst case scenario with abstraction rates close to the upper limit of the recommended yields obtained through the local pumping test analysis. As a result, the predictive simulation run reveals a wide-ranging cone of depression, extending approximately 30 km north to south along the well fields and up to 18 km east to west (considering a 2 m cut-off value), due to the distribution of the well fields as shown in Figure 16. The clearly anisotropic zones of influence or groundwater drawdown are due to the presence of dykes with lower permeabilities resulting in the compartmentalisation of the aquifer system.

The drawdown cone in the optimised Scenario (2a) is smaller in extent and depth (Figure 17). The cone of dewatering is expectedly more pronounced in the central well fields (No. 2). The final dewatering cone of Scenario (2b) (Figure 18) is similar to that of Scenario (2a) with subtle differences in local drawdown in the vicinity of the 7 short term production boreholes (namely SD1-09, SD-25, SD1-19, SD1-22, SD1-26, SD1-40 and SD1-43, which were already inactive for 4 years at the visualised time of 2030). The simulated drawdown behaviour for each well field borehole (Scenario 2b) is shown in Appendix A, while a summary of the drawdown for each scenario is given Table 9. Based on the simulation results, a regional drawdown of the water table between 4 and 7 m are expected for the different well fields. The simulated drawdown behaviour for the proposed long term monitoring boreholes (Scenario 2b) is shown in Appendix B. The predicted drawdown on the existing boreholes (as a result of the SD1 well field dewatering cone) identified during the hydrocensus is shown in Appendix C.

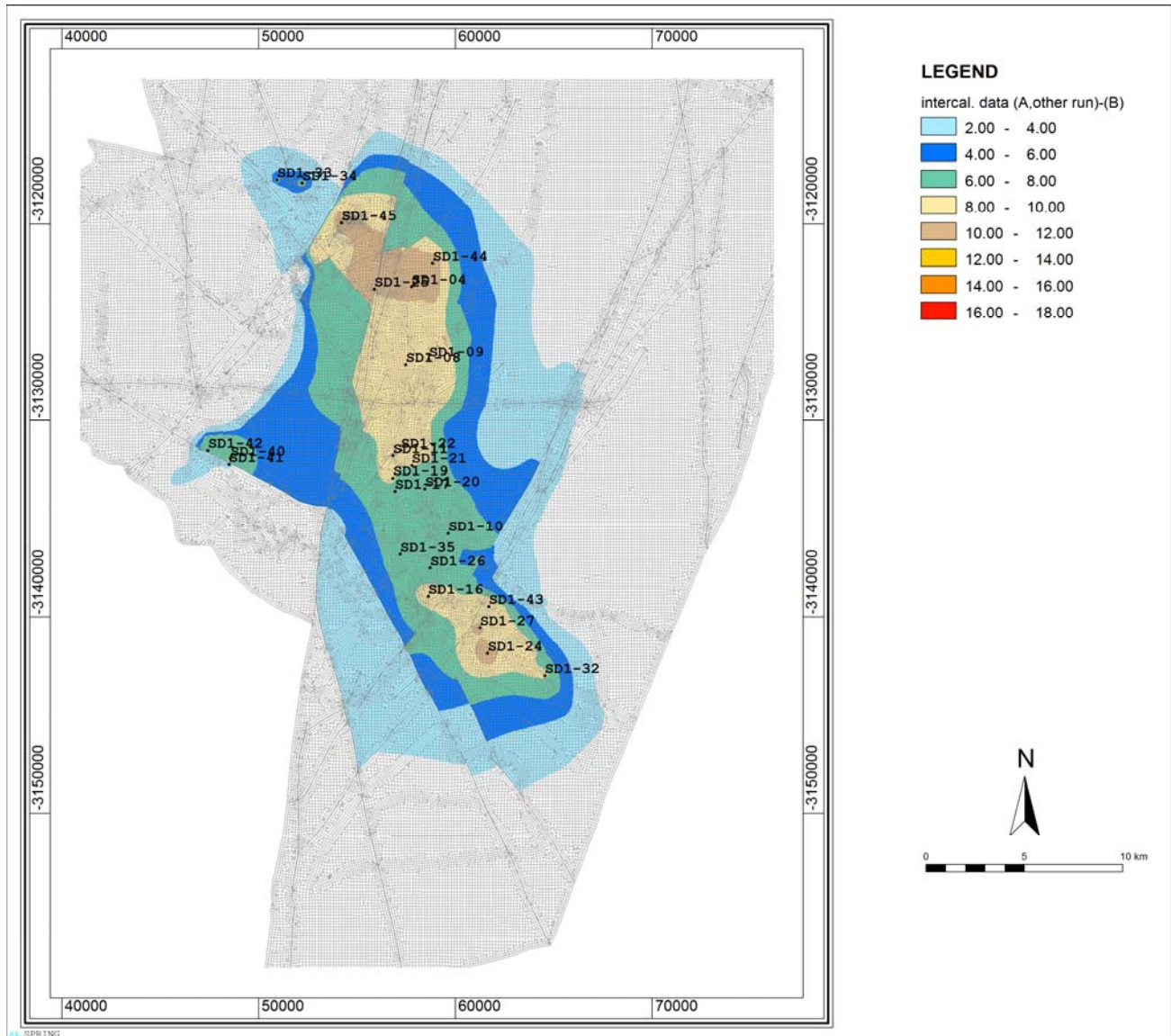


Figure 16: Cone of dewatering [m] due to groundwater abstractions from the SD1 well field, Scenario 1.

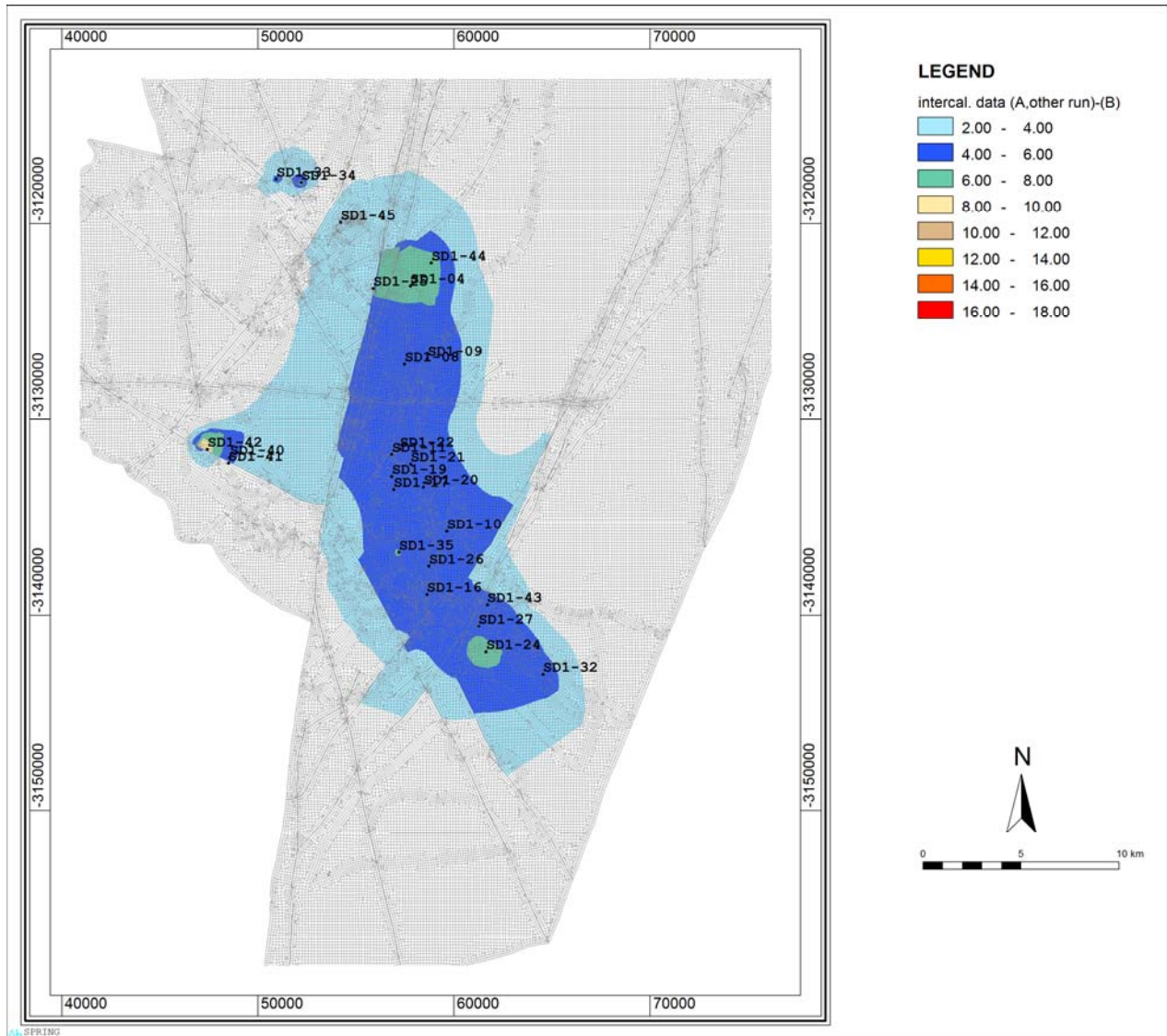


Figure 17: Cone of dewatering [m] due to groundwater abstractions from the SD1 well field, Scenario 2a.

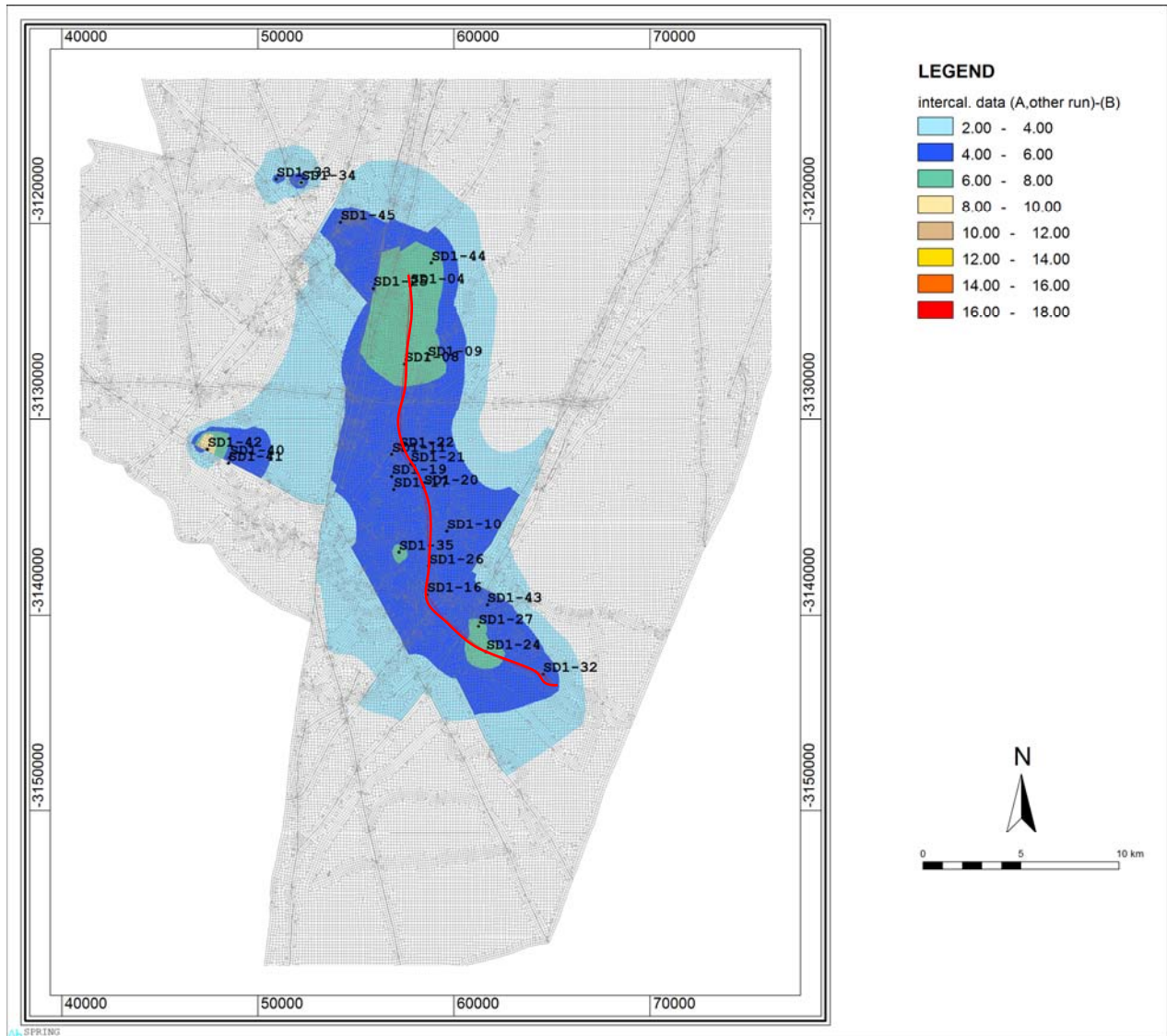


Figure 18: Cone of dewatering [m] due to groundwater abstractions from the SD1 well field, Scenario 2b (red line shows cross-section).

Table 9: Summary of simulated total water table drawdown at the end of the predictive period (February 2030) for the three simulated scenarios.

Well field No.	BH no.	Scenario 1 Drawdown (m)	Scenario 2a Drawdown (m)	Scenario 2b Drawdown (m)
Danielskuil	SD1-33	11.3	10.2	10.4
	SD1-34	17.3	16.0	16.3
	SD1-45	10.7	3.4	4.5
Well field No 1	SD1-04	10.1	6.0	6.6
	SD1-08	9.4	5.6	6.1
	SD1-09	9.4	5.3	5.8
	SD1-25	11.5	3.3	4.4
	SD1-44	10.5	6.4	7.0
Average Drawdown (m)		10.2	5.3	6.0
Well field No 2	SD1-10	7.3	5.4	5.8
	SD1-11	8.2	5.1	5.5
	SD1-16	8.7	5.4	5.7
	SD1-17	8.3	5.4	5.8
	SD1-19	8.1	4.9	5.3
	SD1-20	7.8	5.3	5.7
	SD1-21	8.1	5.1	5.5
	SD1-22	8.1	5.0	5.4
	SD1-26	7.4	5.2	5.6
	SD1-35	7.1	7.6	8.0
Average Drawdown (m)		7.9	5.4	5.9
Well field No 3	SD1-24	14.3	8.8	8.9
	SD1-27	10.0	5.8	6.0
	SD1-32	9.3	6.0	6.1
	SD1-43	9.8	5.2	5.4
Average Drawdown (m)		10.9	6.4	6.6
Well field No 4	SD1-40	10.5	5.0	5.6
	SD1-41	2.3	1.8	1.9
	SD1-42	6.0	12.7	13.5
Average Drawdown (m)		6.3	6.0	7.0

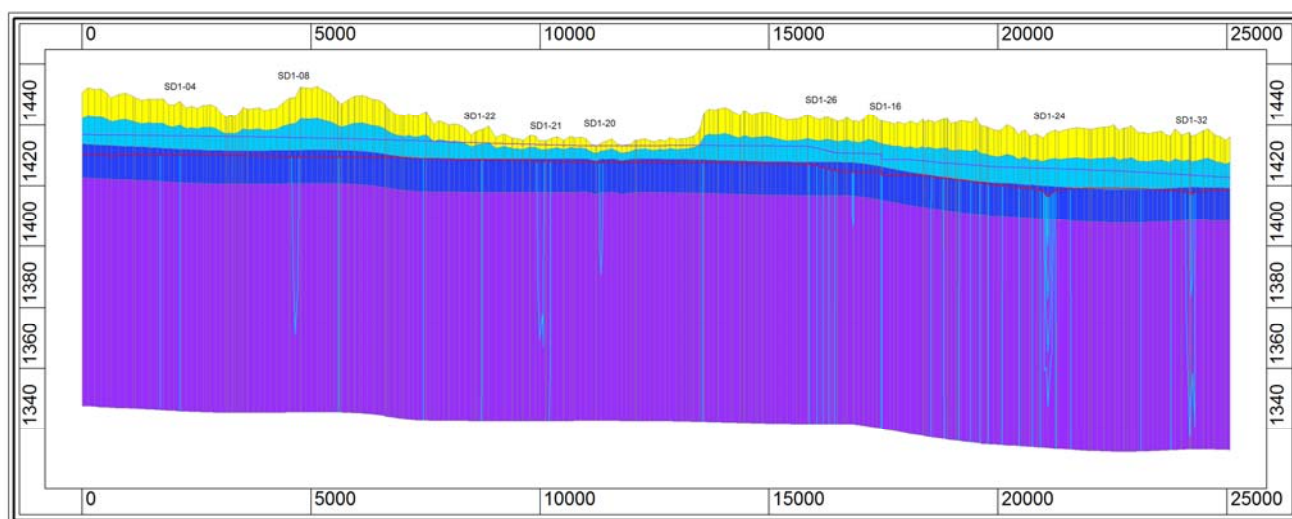


Figure 19: Cross-section of production boreholes from North to South (Refer to Figure 18 for section line).

5.6. IMPACTS ON THE WATER BALANCE ASSOCIATED WITH THE SD1 WELL FIELD

The impacts associated with the SD1 well field for the proposed optimal scenario (2b) will be discussed in the following sections in terms of the deviations from the base case scenario 0 (no well field abstractions). Based on the outcome of the water level drawdown and extent of the dewatering cone a decision was made by the client to put forward scenario 2b as the recommended well field abstraction rate.

5.6.1. Predicted impact on water balance

The change in the predicted water balance compared to the base case (no well field abstractions) for scenario 2b is shown in Table 10. The abstractions from the SD1 well fields results in a change of storage together with a reduction in flows across the outflow boundaries (to downstream catchments) and groundwater contributions to drainages and pans. If the outflows are consistently greater than the inflows, water will be taken from storage, and this manifests itself as an overall decline in groundwater levels. The in- and outflows for the simulation period is shown in Figure 20, while the net change in storage for the base case (no well field abstractions) compared to Scenario 2b is shown Figure 21. The total abstraction from the model domain amounts to approximately 65 % of the average recharge of 1,082,203 m³/month (13 Mm³/annum) for the simulation period.

Table 10: Simulated water balance (Transient State - 2030) (Scenario 2b)

Regional Water Balance	Scenario 2b	Base Case	Diff. From Base Case
Inflow	m³/month	m³/month	m³/month
Recharge	870 492	870 492	
Outflow	m³/month	m³/month	m³/month
Spring Discharge	-27 709	-31 102	-3 393
Borehole Abstractions	-695 639	-231 797	463 842
Contribution to Drainages, pans and potential evapotranspiration	-421 928	-452 708	-30 781
Outflow Boundary	-306 442	-354 014	-47 572
Idwala Pit Inflows	-20 472	-25 439	-4 967
Total Outflow	-1 472 189	-1 095 060	
Change In Storage	-601 697	-224 568	377 129
Total Outflow	-870 492	-870 492	

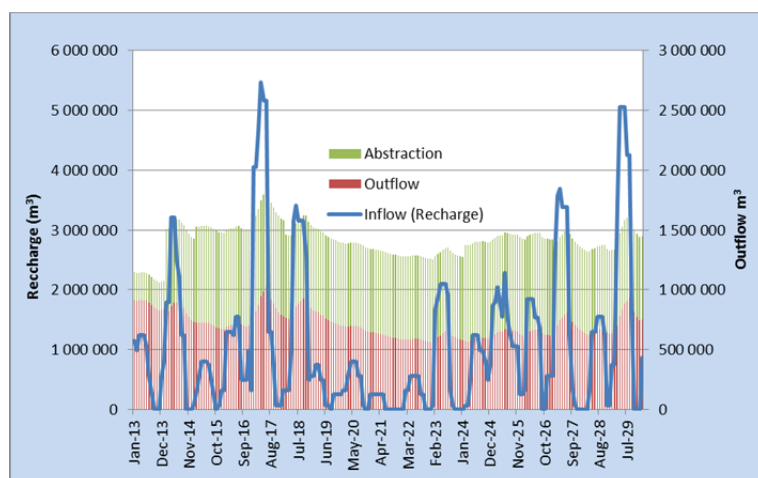


Figure 20: Simulated in- and outflows for the modelled scenario 2b.

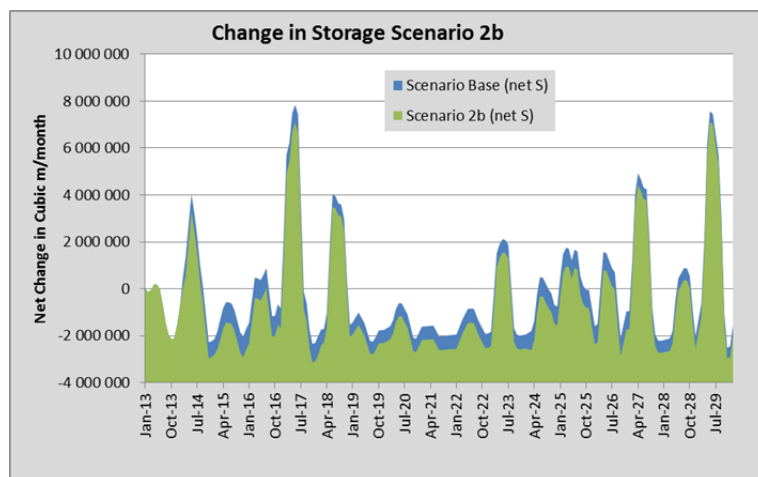


Figure 21: Net change in storage for Scenario 2b compared to the base case.

5.6.2. Estimated impact on downstream catchments

The SD1 well fields (Scenario 2b) will reduce regional groundwater outflow gradually over time until a new (dynamic) equilibrium of recharge and outflow is established (Figure 22). However, it must be emphasised that the change in outflow changes for each time period and that the change in outflow from the first time step (2013) to the last (2030) results in a net change of 2,924 m³/month as a result of the variable recharge and subsequent changes in aquifer storage. The boundaries most affected by the SD1 well fields are the south eastern- and south western outflow (refer to Figure 4) boundaries (Table 11).

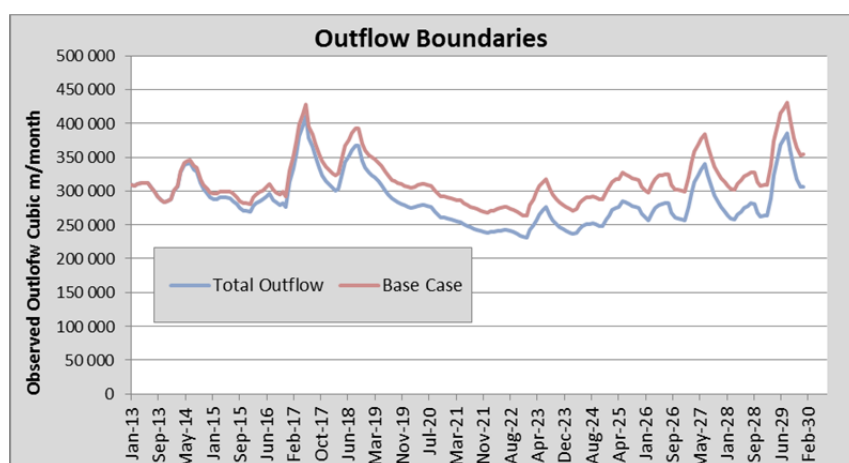


Figure 22: Simulated mass flow rates across the outflow boundaries over time for scenario 2b.

Table 11: Simulated reduction in outflow for each outflow boundary (Transient State - 2030) (Scenario 2b)

Outflow Boundary	Scenario 2b in m ³ /month
North Outflow	0
North East Outflow	0
South East Outflow	-15 567
South Outflow	-93
West Outflow	-194
South West Outflow	-31 718
Total	-47 572

5.7. BOREHOLE PROTECTION ZONES (STEADY STATE WITH SD1 ABSTRACTION)

A wide variety of techniques can be used to determine protection zones, varying from simple analytical methods to complex numerical transport models (EPA, 1993). Numerical simulations of the groundwater system offer the best available analysis of the flow system and delineation of the zone of contribution (ZOC) for a given well. In this study, the calibrated well field model was used to delineate commonly used protection zones to achieve the following levels of protection (Jolly and Reynders, 1993; Chave et al, 2005) (refer to Figure 23):

- A *Wellhead Operational Zone* immediately adjacent to the site of the borehole or well field to prevent rapid ingress of contaminants or damage to the borehole (also referred to as the '*Accident Prevention Zone*')
- An *Inner Protection Zone* based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the '*Microbial Protection Area*')
- An *Outer Protection Zone* based on the expected time required for dilution and effective attenuation of slowly degrading substances to an acceptable level. A further consideration in the delineation of this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.
- A further much larger zone, the *Total Capture Area*, sometimes covers the total catchment area of a particular abstraction area where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.

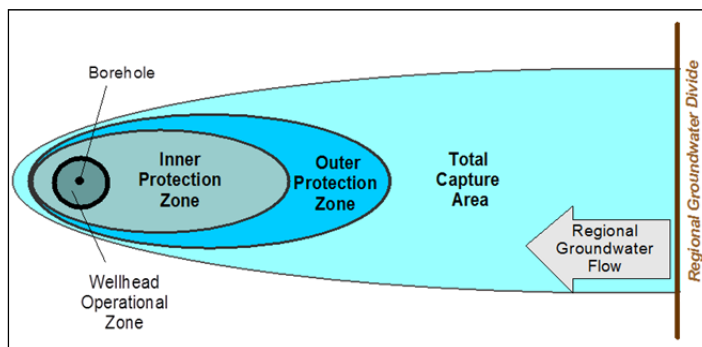


Figure 23: Common protection areas delineated around water supply boreholes (DWA, 2008).

The developed model was used in combination with the reverse particle tracking method to delineate the time-of-travel based capture zones of the abstraction wells. The time-of-travel capture zones were used to rank the degree of risk based on the expected travel time of a non-retarded contaminant to reach the water supply wells. The following criteria were used:

- Zone 1 – Wellhead protection zone – 50 m (fixed radius)
- Zone 2 – Inner protection zone – 100 day time-of-travel
 - Based on the assumption that enteric viruses survive in water on average 100 days.
 - This zone also includes the time required to ensure the natural or appreciable reduction in microbiological organisms, which is 50 days (EPA, 1993).
- Zone 3 – Outer protection zone – 10 year time-of travel
 - In the case of severe pollution (e.g. hazardous spill) within the recharge area of the well fields, a delay in groundwater abstraction from the aquifer of at least 10 years is needed (EPA, 1993).
- Zone 4 – Capture zone – The cumulative catchment area of the SD1 well fields were delineated based on the premise that all water within the zone will eventually reach the production wells (< 50 years).

The delineated protection zones are shown in Figure 24. The protection zones of each well were captured separately, but combined for protection zones 3 and 4 to account for their general overlap in the different well fields. The main protection areas are expectedly elongated towards the upstream catchment areas of the well fields.

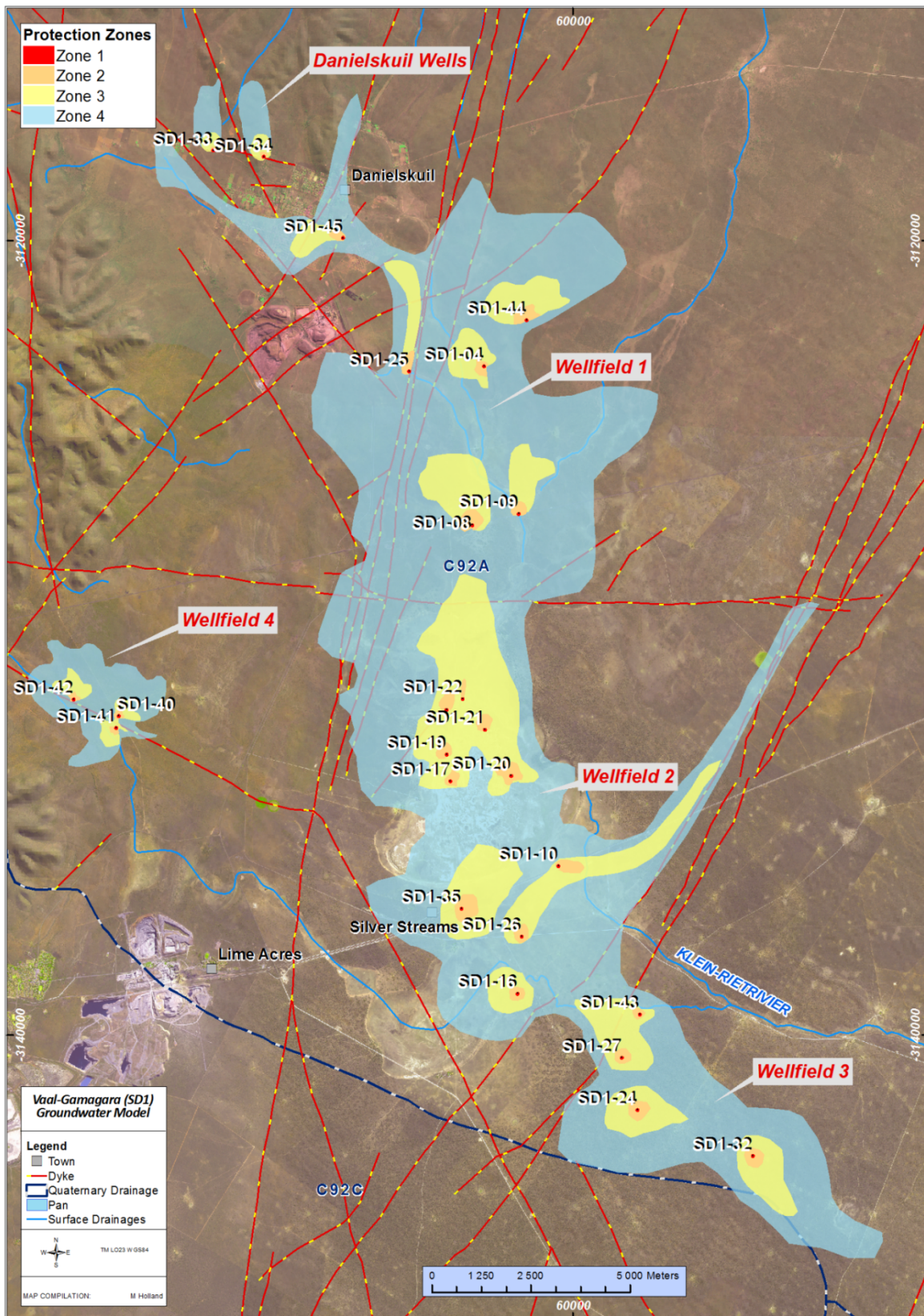


Figure 24: Groundwater protection zones for the SD1 well fields.

6. SUMMARY AND RECOMMENDATIONS

6.1. SUMMARY

Delta H (Delta-H Water System Modelling Pty Ltd) has been appointed by Golder Associates Pty Ltd to develop a numerical groundwater flow model for the Vaal Gamagara (SD1) area to assess potential impact of the proposed well fields on the regional groundwater flow, discharge to downstream catchments and to delineate aquifer protection zones. Abstraction rates for the proposed well field were recommended by Golder Associates based on their preceding groundwater exploration programme.

The conceptual hydrogeological model developed by Golder Associates was converted into a 3D numerical model with 4 element layers, with discrete consideration of hydraulic conductivity zones and geological units in the SD1 well field area. The model was satisfactorily calibrated in steady-state and transient state and derived aquifer parameter compare well with data from hydraulic aquifer tests and literature values. Spatially and temporally variable groundwater recharge rates assigned to the model use an exponential rainfall-recharge relationship and reproduce the observed water level fluctuations within reasonable accuracy for the transient calibration period (1986 to 2012).

The calibrated model was subsequently used to simulate the impacts of the proposed SD1 well fields on the groundwater environment. The historical rainfall period from 1996 to 2012 was extrapolated forward for the simulation period from 2013 to 2030 (17 years, 205 time steps). For comparison purposes, three scenarios, an upper limit scenario (1) an optimised scenario (2a) and more likely implementation scenario (2b), which includes two periods of additional abstraction capacity were assessed against a base case or no-go scenario (0) of no abstractions.

The predictive simulation model (scenario 2b) with a maximum abstraction rate of $6.6 \text{ Mm}^3/\text{annum}$ (from 15 long term and 7 short term SD1 production boreholes) reveals a wide-ranging cone of depression (considering a 2 m cut-off value) due to the distribution of the well fields. Simulated drawdowns for the production boreholes range from 4 to 7 m for the SD1 well field region.

Any volume of groundwater extracted by pumping in the SD1 production boreholes will be compensated by a reduction in outflow (along the south eastern- and south western outflow boundary) and a reduced volume of groundwater baseflow (towards drainages and springs). Over the long-term a new equilibrium will be reached and in order to maintain this equilibrium, groundwater abstractions must be balanced by increased recharge (increase in the amount of water entering the system) or reduced discharge (reducing the amount of water leaving the system) (Seward et al., 2006). However, some of the water that is pumped comes from a change in amount of water stored in the subsurface (especially in the drier periods where the abstraction is greater than the difference between the inflow and residual outflow, then an additional yield (change in S) is required to maintain the abstraction). During significant recharge events, changes in outflows and contribution to baseflow continue to occur until the water that was removed from storage is replenished.

Due to the intrinsic heterogeneity of the dolomitic groundwater system the potential impact of the groundwater abstractions on other groundwater users may not be equally distributed (spatially) around the proposed abstraction areas. Further, some surfaces drainages and pans may be perched on a low-permeability substrate (i.e. the calcrete layer), and may not be in hydraulic continuity with the aquifer beneath and therefore not impacted by a drawdown of the water table.

At this stage, seasonal monitoring data for the transient model calibration are only available for the catchment area upstream of the SD1 well field (mainly Danielskuil area). As a result, the confidence in the model calibration and subsequent predictions is regarded as moderate. Once monitoring data over a full hydrological year become available for the SD1 well fields area, the model should be re-calibrated and predictions updated.

The model predictions should therefore be verified once the well field becomes operational and groundwater monitoring data of the subsequent water table drawdown become available. Predicted drawdown figures for later years can significantly be improved by observation data from the earlier years and subsequent updates of the groundwater model.

6.2. RECOMMENDATIONS FOR FUTURE WORK

The following recommendations are given:

- The model should be utilized to develop optimal operational and management rules for the well field, considering their impact on the regional water balance and water levels.
- With minimal further customization, the model can also be expanded to a mass transport model to simulate water quality impacts across the entire model domain.
- The model should be re-calibrated once a full hydrological year of monitoring data for the SD1 well field becomes available.
 - o Site-specific groundwater and rainfall monitoring data are vital for a reliable transient calibration of the model and to understand and simulate the aquifer responses to abstraction and recharge at higher confidence.
 - o Monitoring the long-term groundwater level changes in a borehole that is not too close to be directly affected by individual production boreholes provides a very useful indication of the 'health' of the water balance in the aquifer.
 - o In this regard a well field management plan should be developed which considers mitigation measures (or temporary cessation of abstraction), if the water level near a receptor (such as a wetland/pan) falls below a fixed threshold.
 - o Annual review of the model predictions and model update if required.

7. REFERENCES

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8. DISCLAIMER

Delta-H Water System Modelling Pty Ltd (Delta H) has executed this study along professional and thorough guidelines, within their scope of work. The model development is solely based on aquifer data (water level measurements) and a conceptual model provided by others. Delta H does not accept any liability for the accuracy or representivity of the data provided by others.

No representation or warranty with respect to the information, forecasts, opinions contained in neither this report nor the documents and information provided to Delta H is given or implied. Delta H does not accept any liability whatsoever for any loss or damage, however arising, which may directly or indirectly result from its use.

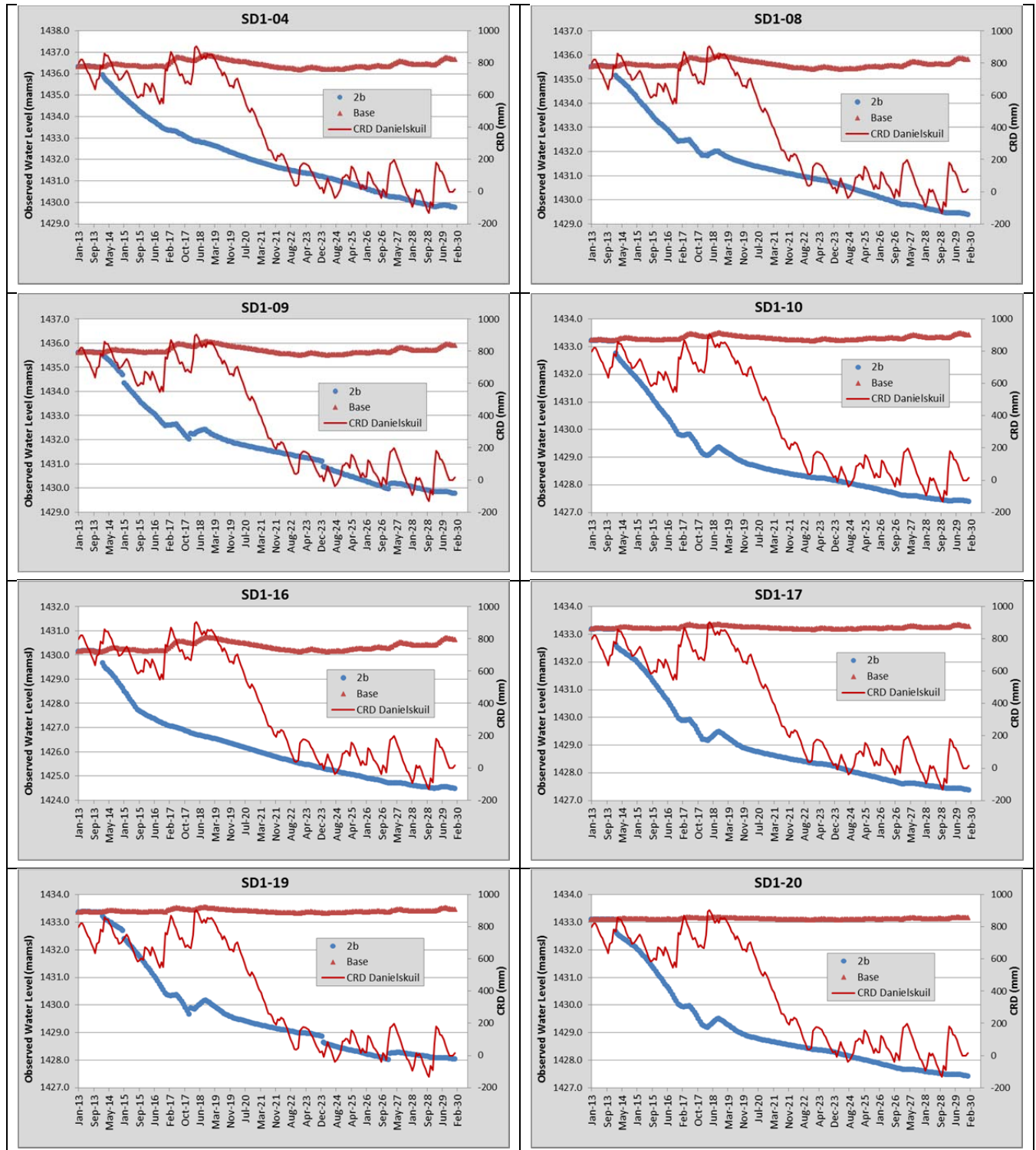
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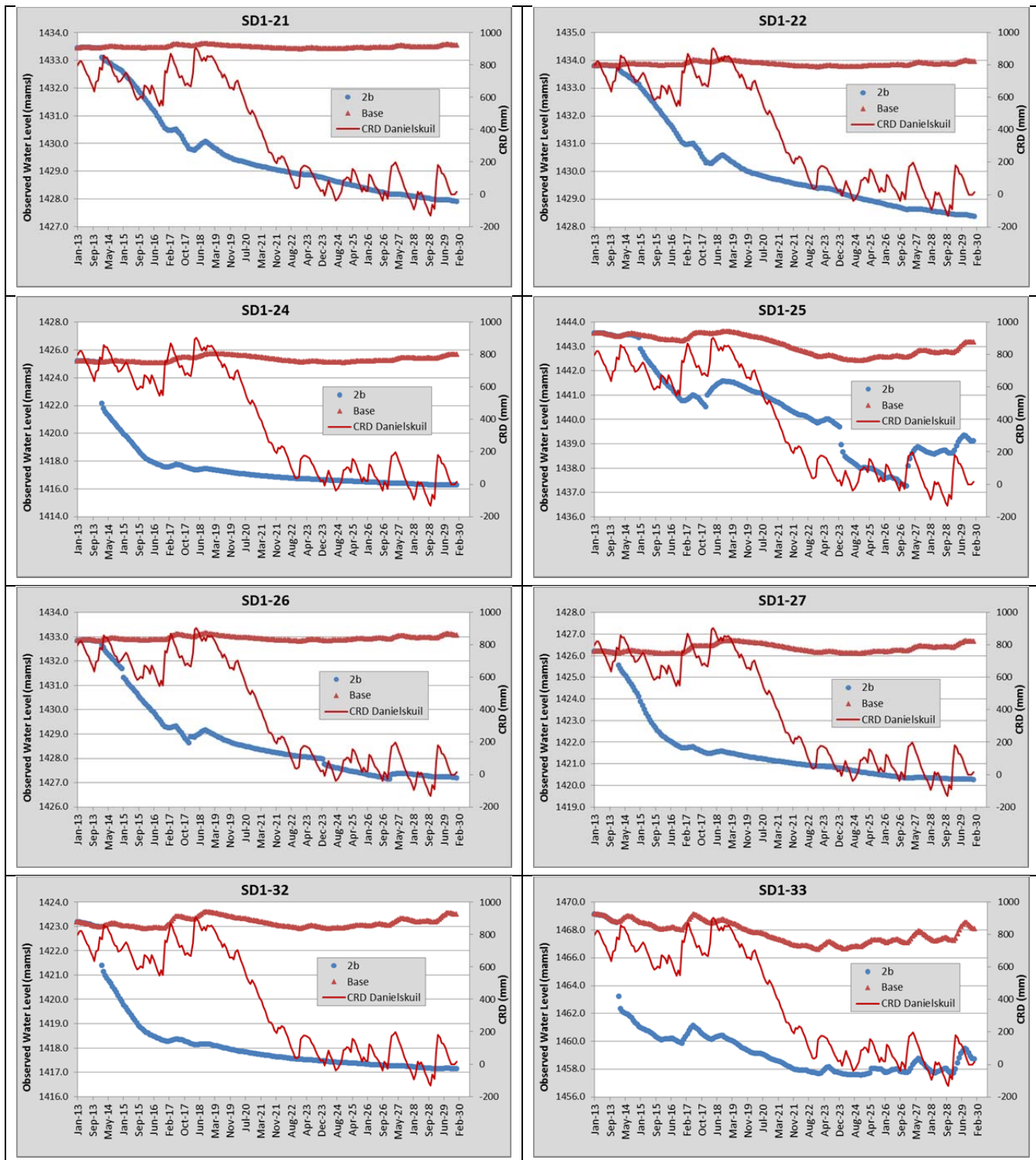
9. DECLARATION OF INDEPENDENCE

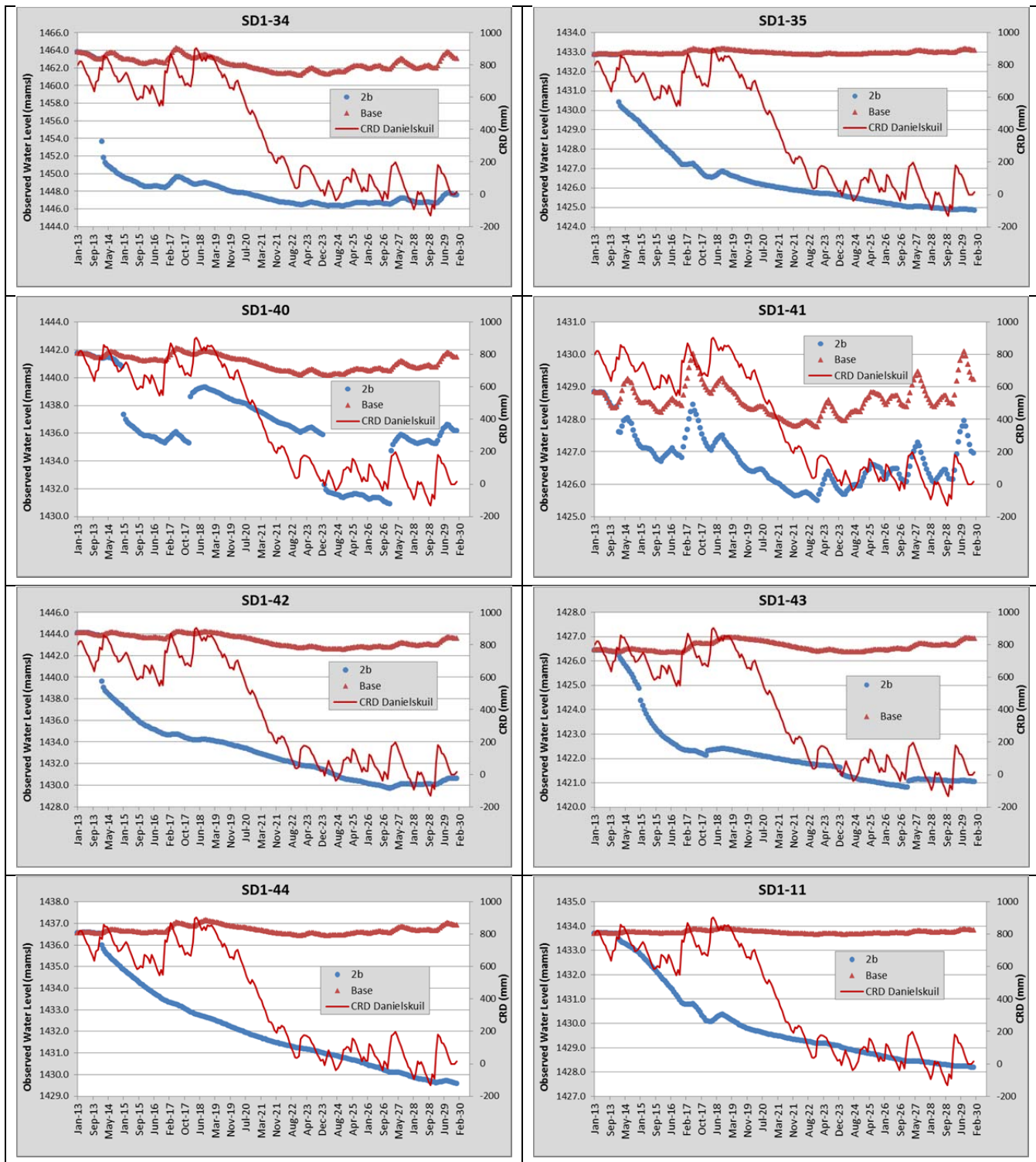
Delta-H Water System Modelling Pty Ltd (Delta H) and its associates have no direct or indirect business, financial, personal or other interests in the activity, application or appeal other than fair remuneration for work performed in connection with that activity, application or appeal and there are no circumstances that may compromise the objectivity of the persons performing such work. The remuneration of the services provided by Delta-H is in no way contingent upon the conclusions or opinions expressed in this report.

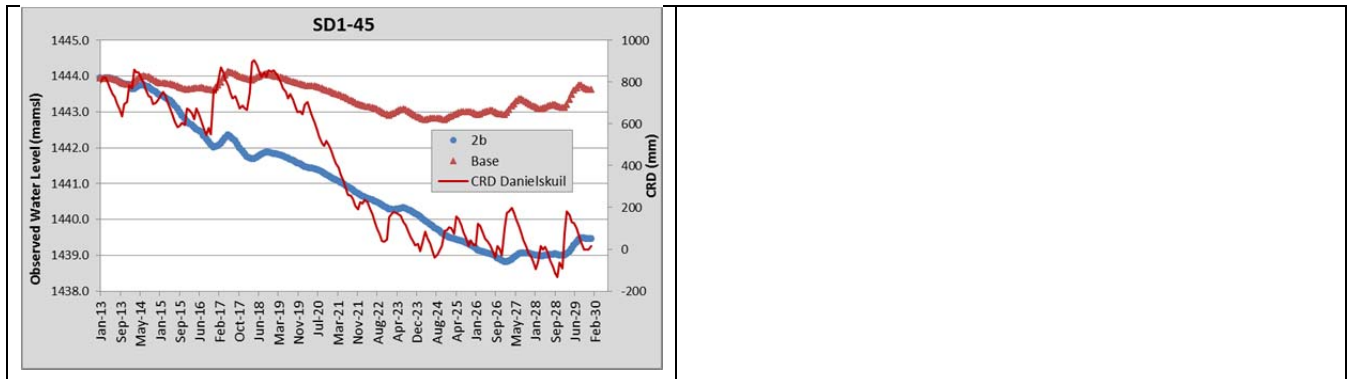
APPENDIX A - DRAWDOWN FIGURES (PRODUCTION BOREHOLES)

Scenario 2b



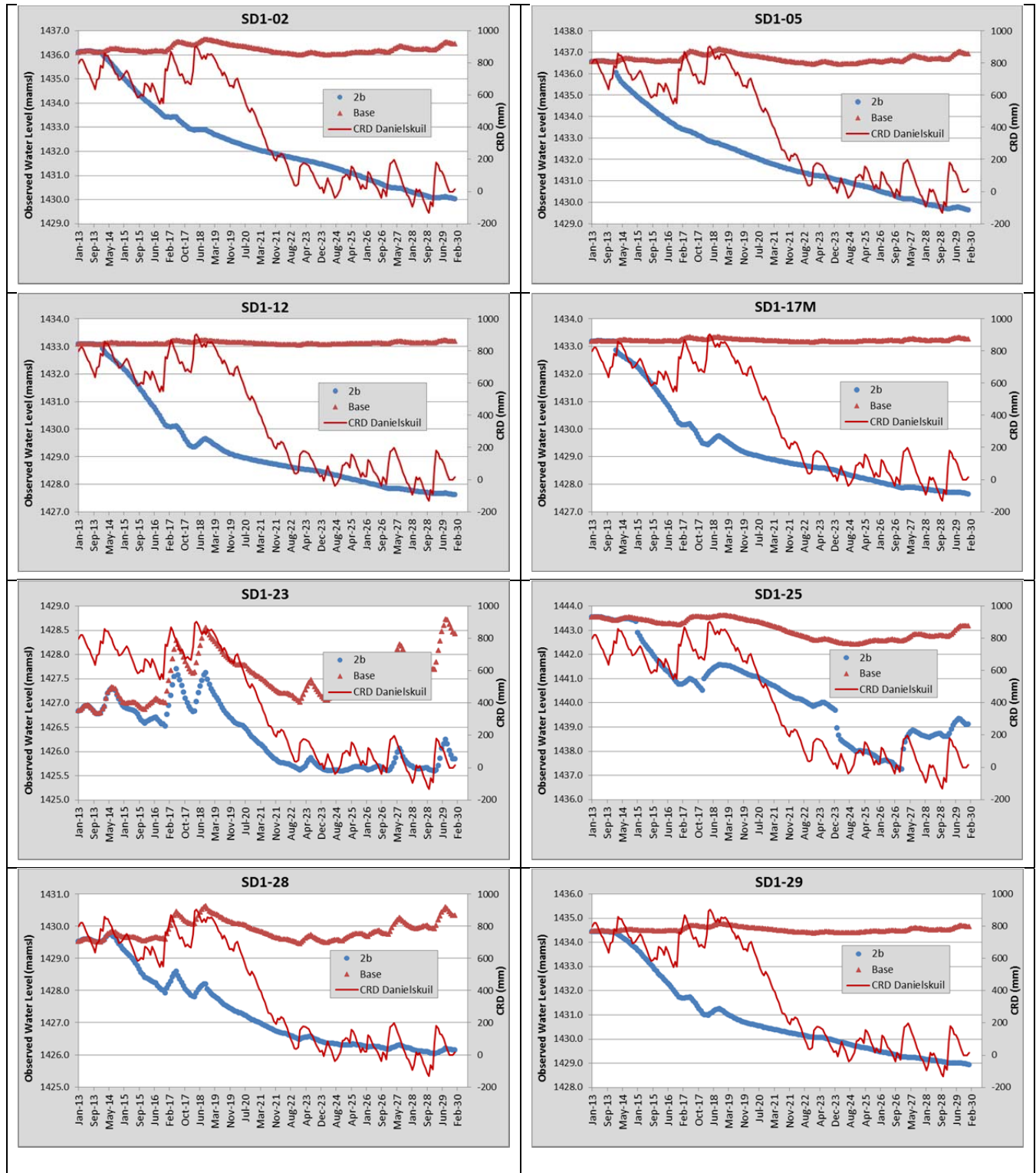


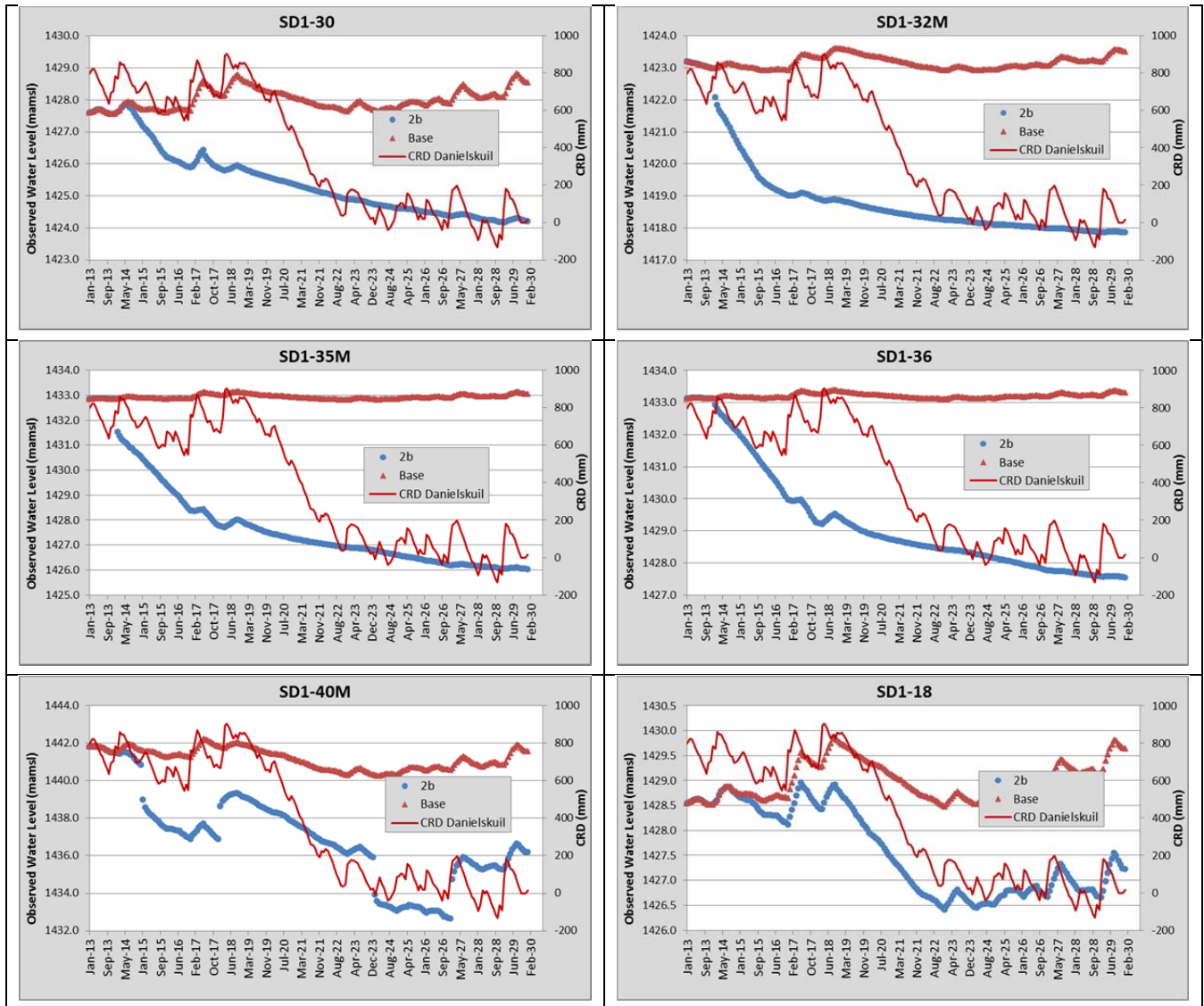




APPENDIX B – DRAWDOWN FIGURES (MONITORING BOREHOLES)

Scenario 2b





APPENDIX C – DRAWDOWN TABLE AND FIGURES (HYDROCENSUS BOREHOLE)

Hydrocensus Drawdown Summary Table

X_LO23WGS	Y_LO23WGS	ID	Drawdown (m from base case)
63040	-3141552	SD1-GAA003	5.26
60787	-3141750	SD1-GAA005	5.61
59000	-3138446	SD1-GAA019	5.42
52281	-3118086	SD1-GAA259	5.42
58934	-3133943	SD1-GAA263	5.42
56470	-3120269	SD1-GAA240	4.32
56423	-3120269	SD1-GAA241	4.33
55582	-3118822	SD1-GAA244	4.11
55670	-3118804	SD1-GAA243	4.07
55601	-3118707	SD1-GAA245	3.96
55635	-3119057	SD1-GAA239	4.27
61684	-3140351	SD1-GAA004	5.53
60635	-3137383	SD1-GAA007	4.15
62544	-3138245	SD1-GAA009	1.95
62543	-3138237	SD1-GAA010	1.95
66510	-3144263	SD1-GAA014	2.06
60168	-3134314	SD1-GAA017	5.29
57901	-3137795	SD1-GAA018	5.67
59874	-3140478	SD1-GAA020	4.32
59812	-3140525	SD1-GAA021	4.27
59829	-3140505	SD1-GAA022	4.28
58707	-3143971	SD1-GAA023	1.71
53718	-3133088	SD1-GAA024	3.87
53744	-3133051	SD1-GAA025	3.89
53737	-3133033	SD1-GAA026	3.89
56429	-3131968	SD1-GAA027	5.41
56399	-3132088	SD1-GAA028	5.4
57319	-3134782	SD1-GAA029	5.48
57871	-3126909	SD1-GAA058	5.91
57876	-3126904	SD1-GAA059	5.91
59544	-3124801	SD1-GAA060	4.6
57567	-3125208	SD1-GAA061	6.05
57570	-3125247	SD1-GAA062	6.04
55002	-3128499	SD1-GAA063	5.15
56394	-3129891	SD1-GAA064	5.43
56893	-3140809	SD1-GAA069	1.42
57808	-3139932	SD1-GAA070	4.15
56398	-3144628	SD1-GAA071	0.27
55502	-3134086	SD1-GAA072	4.42
55390	-3134208	SD1-GAA073	4.26
55377	-3134558	SD1-GAA074	4.11
53591	-3133810	SD1-GAA075	3.41
53544	-3133867	SD1-GAA076	3.39
53533	-3133906	SD1-GAA077	3.35
53520	-3133964	SD1-GAA078	3.27
53494	-3134451	SD1-GAA079	2.22
52908	-3133822	SD1-GAA080	3.91
56799	-3137119	SD1-GAA100	5.4
55407	-3138519	SD1-GAA101	1.49
57197	-3137670	SD1-GAA102	5.59
56961	-3137780	SD1-GAA103	5.05
56943	-3137773	SD1-GAA104	5.02
56940	-3137781	SD1-GAA105	5.01
57018	-3137688	SD1-GAA106	5.25
55884	-3136815	SD1-GAA107	4.13
55029	-3140260	SD1-GAA128	1.27
55051	-3140263	SD1-GAA129	1.27
53794	-3134960	SD1-GAA188	2.13
54690	-3136162	SD1-GAA189	3.18
56281	-3135893	SD1-GAA190	4.87
55677	-3118935	SD1-GAA242	4.23
55949	-3123349	SD1-GAA257	4.26
55866	-3122900	SD1-GAA258	4.43
57925	-3118599	SD1-GAA226	2.34
57494	-3120167	SD1-GAA225	3.46
51378	-3132952	SD1-GAA265	4.05
50555	-3131598	SD1-GAA264	4.18

