



IAH AUSTRALIA

WA chapter monthly talk
Wednesday, 17-th of September 2014

Analytical modelling of groundwater wells and well systems: how to get it right?

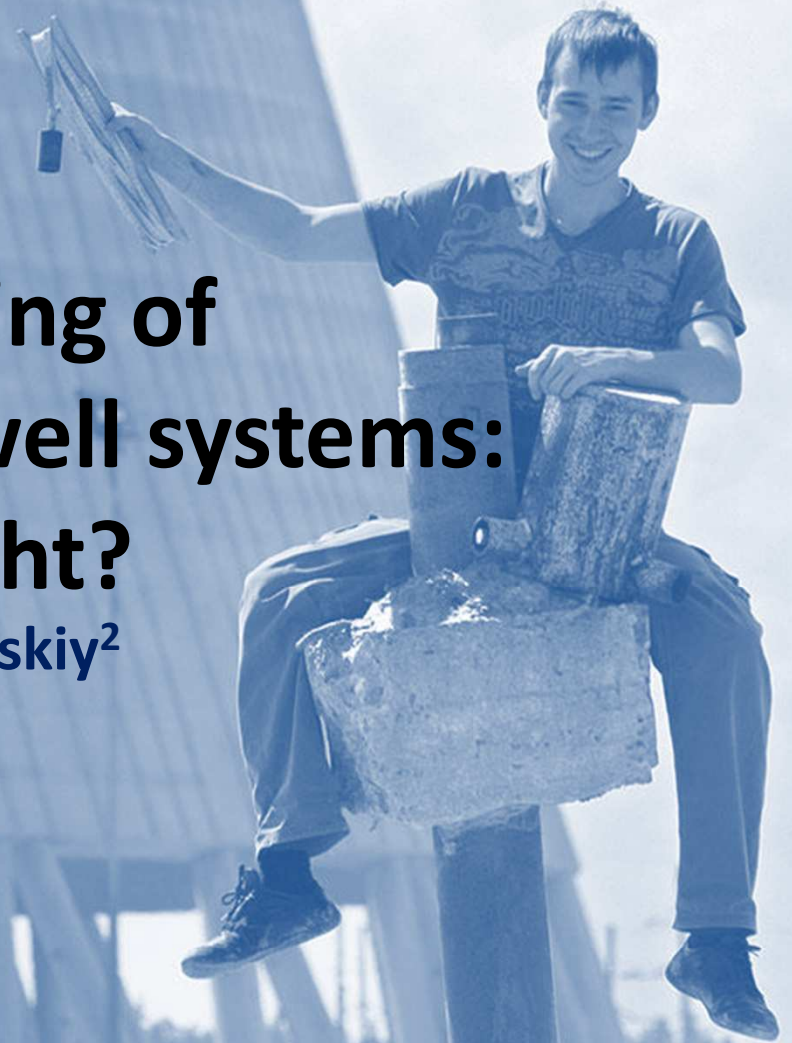
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Why talk about pump tests interpretation?

Often this is the only data available for water supply and dewatering

Obtaining aquifer test data is expensive and time-consuming

- n x 10,000 – n x 100,000 AUD – average test cost
- Weeks of planning, drilling and testing in the field.

But..

Interpretation time – hours. We attempt to do it quickly and save money

Better interpretation – more reliable groundwater predictions!

IAH 2013 International Congress paper: Todd Hamilton and Milo Simonic “Reducing uncertainty in test pumping analysis”

Outline

- Common pitfalls in pump test interpretations and case studies
- Analytical method for well systems design
- MODFE and RADFLOW numerical codes for solving 2D axis-symmetrical numerical flow models

Software

Aqtesolv 4.5

HydroSOLVE, Inc, <http://www.aqtesolv.com/>

Feflow 6.1

DGI-WASY GmbH, www.feflow.com

Ansdimat 8.5

Institute of Environmental Geosciences of the Russian Academy of Sciences,
<http://www.ansdimat.com/>



ANSDIMAT – pump test interpretation by curve-matching

The image displays the ANSDIMAT v.8.4.3 software interface. The main window shows a conceptual scheme for an unconfined aquifer with an unbounded boundary condition. The diagram includes a well with discharge Q , a water table, and various parameters: S, S_y (storage coefficients), k_z (vertical hydraulic conductivity), k_r (horizontal hydraulic conductivity), z_{w1} and z_{w2} (well depths), z_{p1} and z_{p2} (piezometer depths), l_w (well length), and r (radius). The matching parameters dialog box is open, showing the following parameters:

Parameter	Value	Units
Horizontal hydraulic conductivity	0.8	m/day
Vertical hydraulic conductivity	0.05	m/day
Storage coefficient	0.0001	-
Specific yield	0.25	-

The dialog box also includes an "Isotropic aquifer" checkbox (unchecked) and a "Solver" dropdown menu. The selected solver is "Neuman: drawdown in observation well (average)". Other solver options include "Neuman: drawdown in piezometer", "Boulton: drawdown in observation well", "Boulton: drawdown of the water table", "Moench: drawdown in observation well", "Moench: drawdown in piezometer", "Boulton: drawdown in observation well (2)", and "Moench: drawdown in observation well (finite diameter of pumping well)".

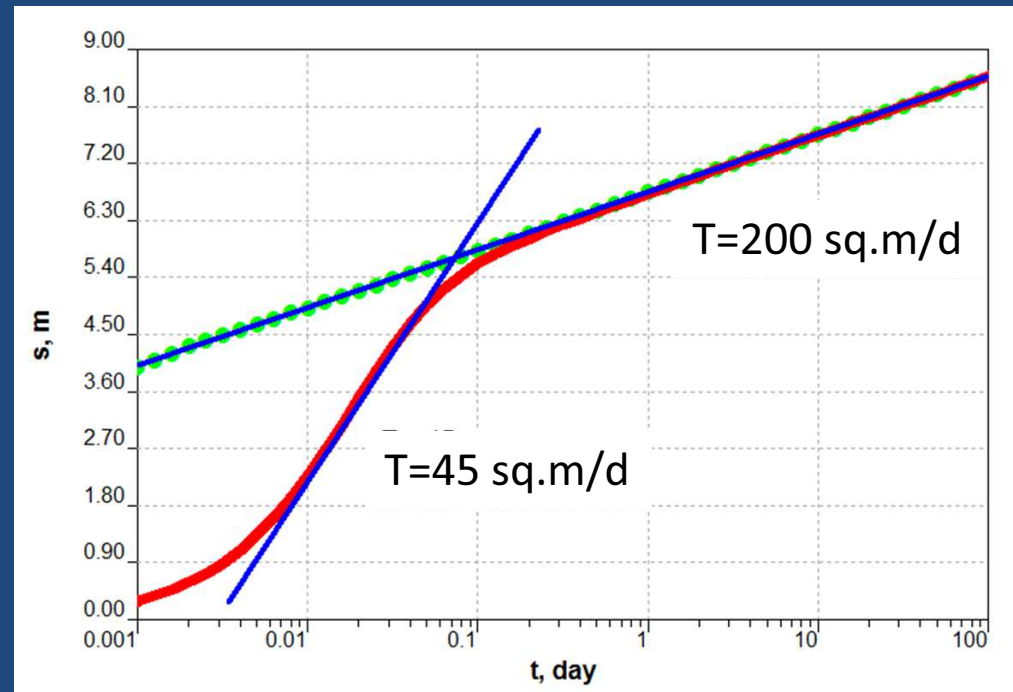
ANDIMAT users



ANDISMAT is officially registered and included in the Russian State Register of computer codes. Certificate #2009614366

Common pitfalls in pump test interpretation by analytical models

- Interpreting unconfined aquifer response by “confined” analytical solution for a wrong time-drawdown interval
- Not accounting for well storage
- Interpreting skin-effect as an aquifer response



- Drawdown in pumping well with well storage
- Drawdown in pumping well without well storage
- Cooper-Jacob approximation

Short-time pump tests – high risk of errors !!

Example 1 – Fitzroy River Catchment Test borehole for water supply

Depth (m bgl)	Graphic + Stratigraphy	Lithological Description	Field Notes	Bore Construction
0		ALLUVIUM: pale brown, silt, sand and gravel, angular to rounded		+0.2-5m: 12" diameter steel collar
10		SHALE: brown, pale grey, extremely weathered, laminar texture		0-5m: 14" diameter air blade
		SHALE: grey, dark grey, moderately to very weathered, laminar texture		
20		SHALE: dark grey, slightly weathered, laminar texture	17m: wet sample after rod change	
30			25m: minor groundwater intersect, Q<0.1L/s	0.5-98: backfill
40			35m: wet sample after rod change	
			41m: wet sample after rod change	
50			53m: wet sample after rod change	+0.2-107m: 175mm ND class 12 uPVC blank casing
60		SHALE: dark grey, fresh, laminar texture; minor sandstone bands	59m: wet sample after rod change	5-149: 12" diameter DC hammer
70			65m: wet sample after rod change	
			71m: dry	
80			77m: wet sample after rod change	
			83m: wet sample after rod change	
90			89m: wet sample after rod change	
			95m: wet sample after rod change	
100		SANDSTONE: pale grey, fresh, subrounded, moderately cemented, fine grained, quartz	101m: wet sample after rod change	98-100m: bentonite seal
		SHALE: dark grey, fresh, laminar texture, minor sandstone bands	107m: wet sample after rod change	
110		SANDSTONE: pale grey, fresh, subrounded, moderately cemented, fine grained, quartz	108m: groundwater file rect	100-149m: gravel pack (+1.6 -3.2mm)
		Interbedded SANDSTONE and SHALE: pale grey, fresh, fine grained, moderately cemented sandstone and dark grey, laminar shale	113m: Q=3L/s, EC=1.24mS/cm@34.1 C, pH=8.34	
120		SANDSTONE: pale grey, fresh, subrounded, moderately cemented, fine grained, quartz	119m: Q=3L/s, EC=1.17mS/cm@33.4 C, pH=8.33	
		Interbedded SANDSTONE and SHALE: pale grey, fresh, fine grained, moderately cemented sandstone and dark grey, laminar shale	125m: Q=5L/s, EC=0.83mS/cm@34.4 C, pH=8.38	107-149m: 175mm ND class 12 uPVC slotted casing
130		SANDSTONE: pale grey, fresh, subrounded, poorly cemented, fine grained, quartz	131m: Q=5L/s, EC=0.75mS/cm@34.9 C, pH=8.39	
		Interbedded SANDSTONE and SHALE: pale grey, fresh, fine grained, moderately cemented sandstone and dark grey, laminar shale	137m: Q=6L/s, EC=0.72mS/cm@35.2 C, pH=8.34	
140		SANDSTONE: pale grey, fresh, subrounded, poorly cemented, fine grained, quartz	143m: Q=6.7L/s, EC=0.72mS/cm@35.5 C, pH=8.35	
150			149m: Q=10L/s, EC=0.59mS/cm@35.3	149m: end of hole
160				

Profile:

0-100 m bgl – confining or semi-confining shale

100-150 m bgl – Poole Sandstone

Poole sandstone – a high yielding aquifer, good water quality (TDS < 1 g/L). It is believed to have a thickness of around 250 m

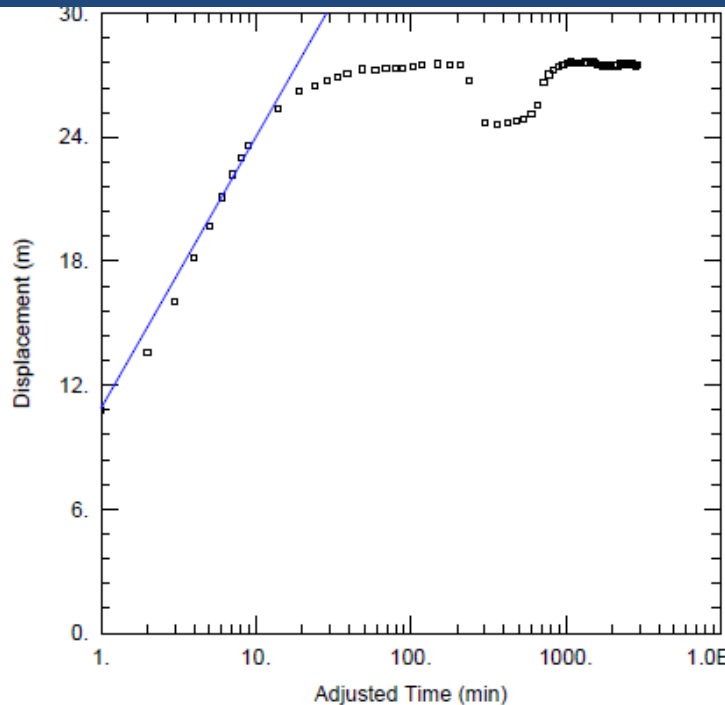
Borehole:

Total depth – 150 m

Screen interval – 100-150 m bgl

48-hour constant rate pump test. Pumping rates were recorded at hourly intervals

Example 1 – original interpretation



CONSTANT RATE

Data Set: Z:\...\JacobConstantRate.aqt

Date: 12/15/10

Time: 09:12:48

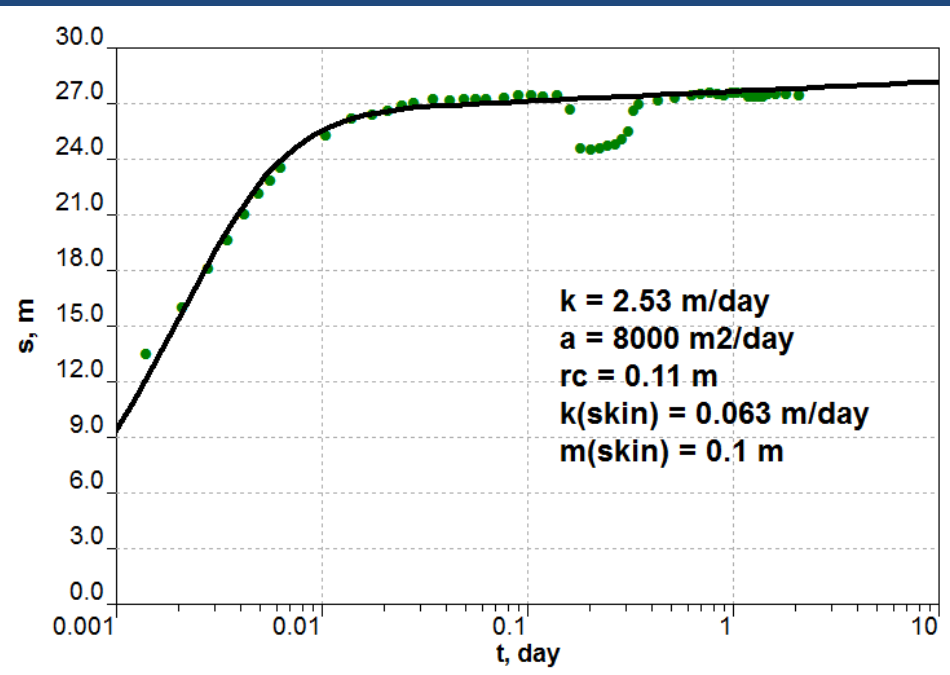
$K=0.14$ m/d or less
(depending on assumed effective thickness).

The value is based on the first interval that reflects well bore storage and skin-effect, but not the aquifer!

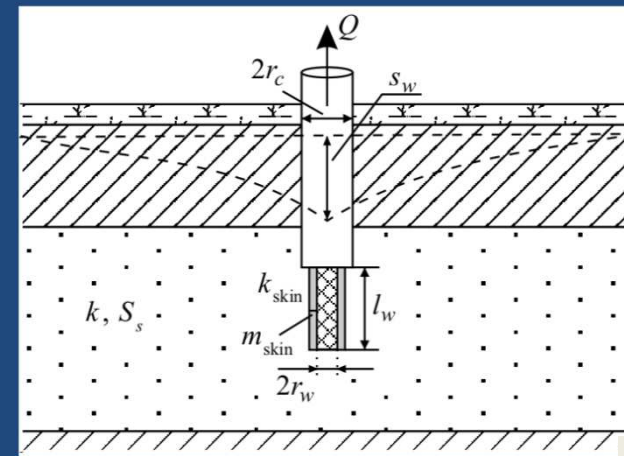
Table 7: Summary of Aquifer Properties

Test Type	Transmissivity (m ² /d)	Aquifer Thickness (m)	Hydraulic Conductivity (m/d)	Method
Constant Rate	6.034	42	0.14	Cooper-Jacob (1946)
Recovery	10.53	42	0.25	Theis (1935)

Example 1 – corrected interpretation



Conceptual scheme
*partially penetrating well in a
 thick confined aquifer,
 Well-bore storage and skin-effect*



Well-bore storage parameter:

$$W_D = \frac{r_c^2}{2r_w^2 S_s l_w}$$

Well-bore skin parameter:

$$W_{skin} = \frac{km_{skin}}{r_w k_{skin}}$$

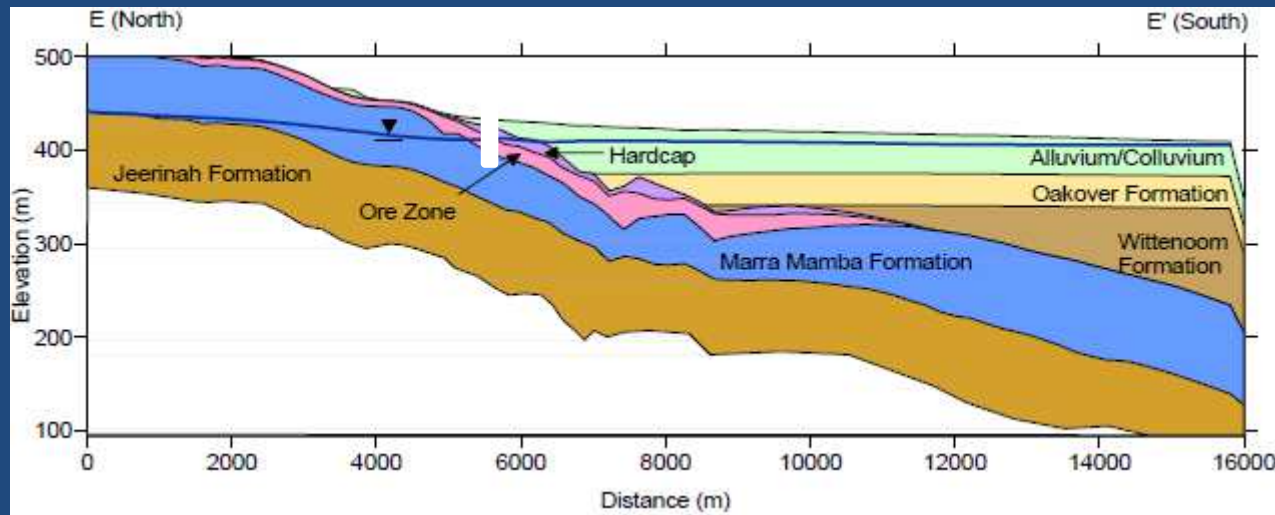
$$s_w = \frac{Q}{4\pi k_r m} f(t, r_w, r_c, m, l_w, L_{Tw}, k_r, k_z, a_r, k_{skin}, m_{skin})$$

Algorithm WTAQ3 (Moench, 1997):

Moench A.F. Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer // Water Resources Research. 1997. Vol. 33, N 6. P. 1397–1407.

Example 2 – Pilbara

Test pumping for mine dewatering



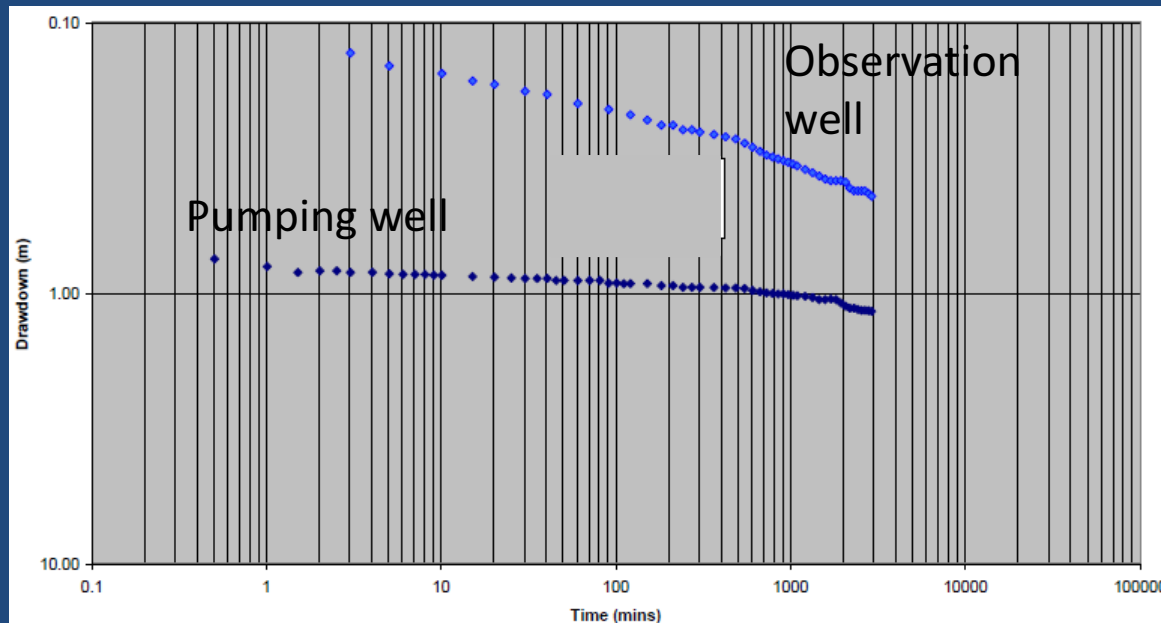
Unconfined aquifer

Profile:

- Alluvium
- Ore Zone (aquifer)
- BIF

Well	Distance from Test Well, m	Total Depth, m	Slotted Interval, m bgl	Lithology
Pumping Well	-	45	12-45	Alluvium, Hardcap, Ore Zone & BIF
Obs Well	15.2	32	20-32	Alluvium, Hardcap, Ore Zone

Example 2 – original interpretation



124 m/d for early time and 38 m/d for late time.

The same results for pumping and observation wells

“Early time data may represent the aquifer while the late time data may represent the underlying shales”

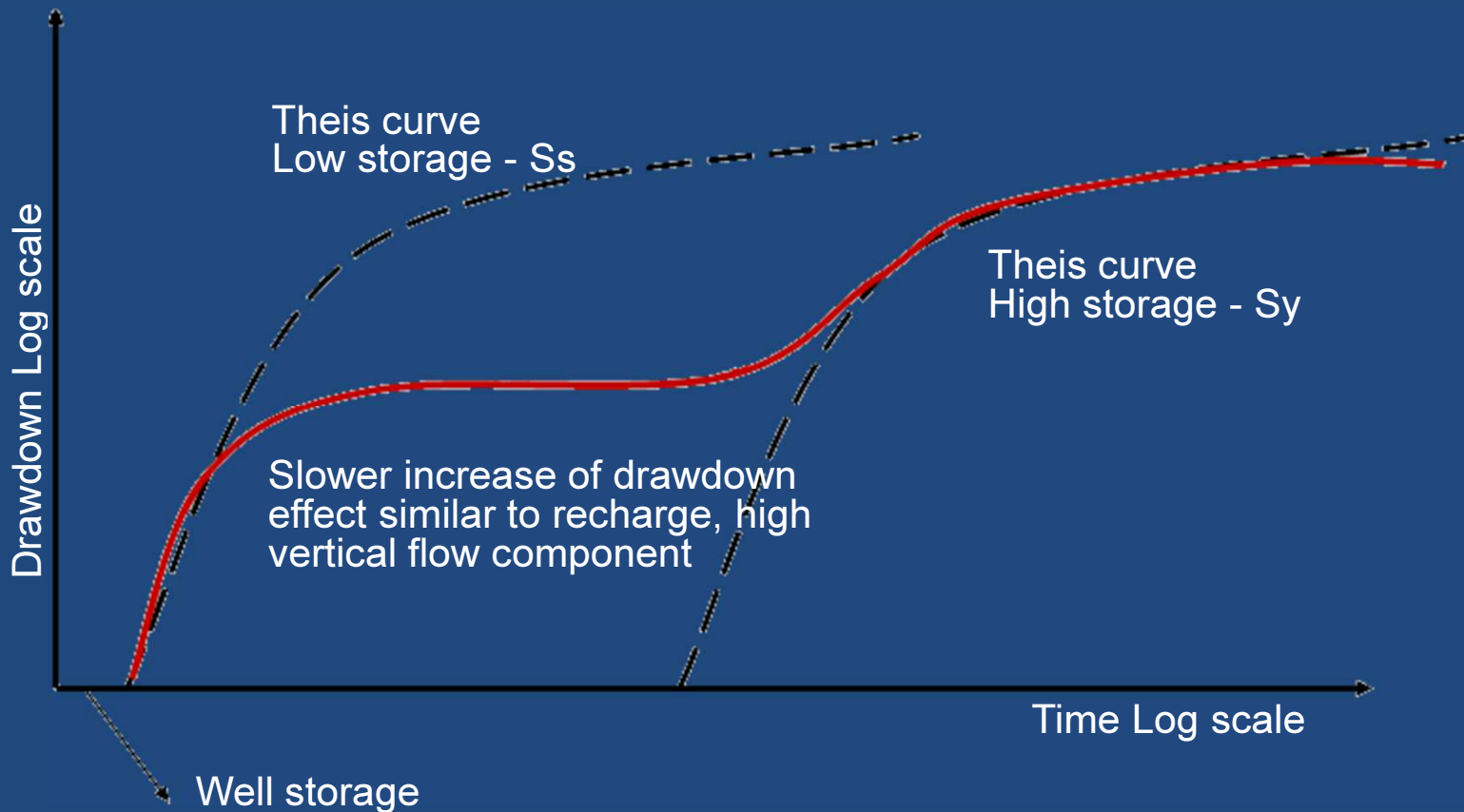
Test Well	Observation Well	Constant Rate Test Transmissivity (m ² /d)	Recovery Test Transmissivity (m ² /d)	Storativity Estimate
		- ^a	- ^a	- ^a
	Pumping	4,090 (early); 1,240 (late)	5,450	-
CB471T	Obs	4,020 (early); 1,190 (late) <i>Theis</i> 3,910 (early) 1,130 (late) <i>Cooper-Jacob</i>	-	6.06 x 10 ⁻⁴ (early); 1.79 x 10 ⁻¹ (late) <i>Theis</i> 6.14 x 10 ⁻⁴ (early); 1.95 x 10 ⁻¹ (late) <i>Cooper-Jacob</i>

Note: a. Insufficient drawdown induced in observation well to enable analysis

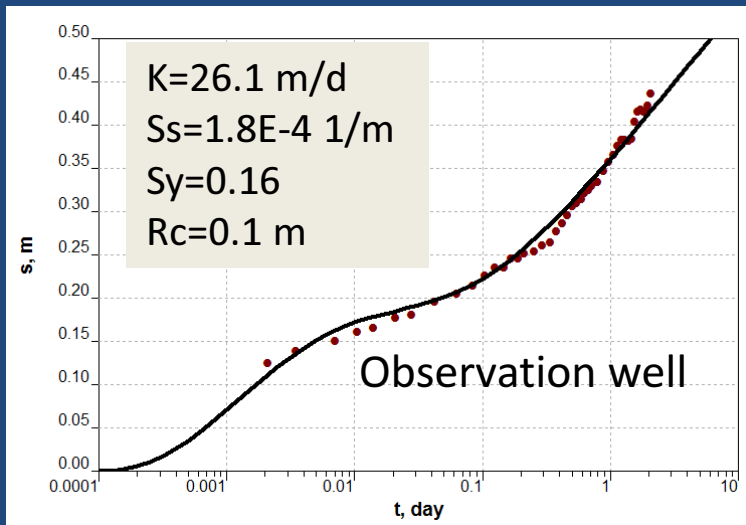
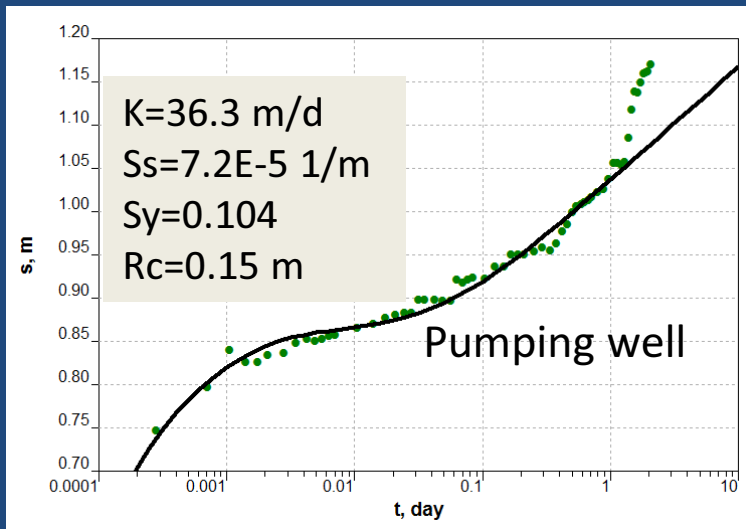
The test pumping analysis confirms the heterogeneity of both the alluvium and mineralised Marra Mamba, but does not provide reasonable estimates of regional hydraulic properties. Actual values used in the numerical modelling are described in Section 6.

Conclusion:
The aquifer is highly heterogeneous. Because of this, the test results are not applicable, so the model used different values

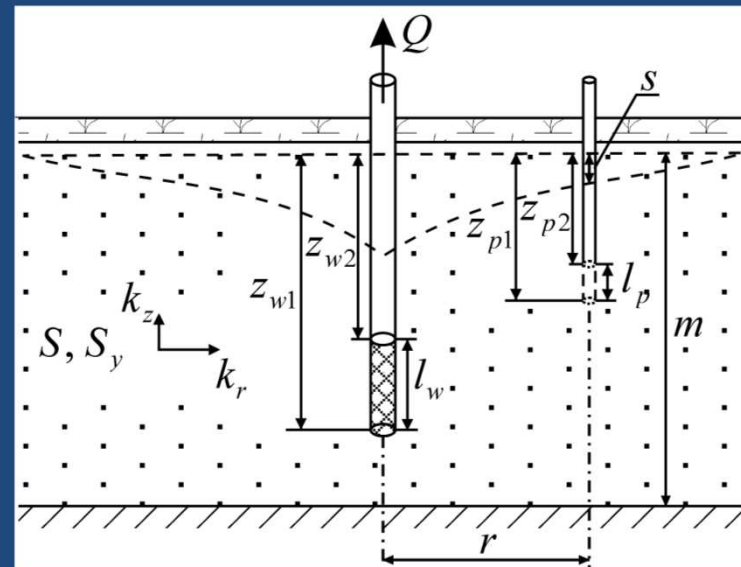
Unconfined aquifer – three stages of drawdown



Example 2 – corrected interpretation



Conceptual scheme
partially penetrating well in an unconfined aquifer



Algorithm: Moench (1997):

$Kh = 26 \text{ m/d} - 36 \text{ m/d}$, rather homogeneous aquifer, though lower-permeability zone or boundary may be present at distance

Marra Mamba heterogeneity

Is it really so high?

Or may be just an artefact of interpretation?

Table 6 – Aquifer Test Results (by Aquifer)

Aquifer	T ¹		K ²		S ³		No. of Tests
	Range	Avg.	Range	Avg.	Range	Avg.	
Tertiary Detritals	59–210	135	4.2–5.3	4.8	1.3x 10 ⁻³ – 4.2 x 10 ⁻⁴	8.6 x 10 ⁻⁴	2
Oakover Fmn.	3460– 5505	4483	115–167	141	3.3 x 10 ⁻³ – 4.4 x 10 ⁻⁴	7.87 x 10 ⁻³	2
Mineralised Marra Mamba Fmn.	1520– 6955	4046	11- 311	226	3.3x 10 ⁻⁵ – 7.9 x 10 ⁻³	5.01 x 10 ⁻³	3
Non-mineralised Marra Mamba Fmn.	18–773	287	1.7–32	13	-	1.7 x 10 ⁻³	3
Marra Mamba Fmn. (all ⁴)	222– 5797	2358	11–386	100	1.4 x 10 ⁻⁴ – 7.7 x 10 ⁻³	2.03 x 10 ⁻³	14

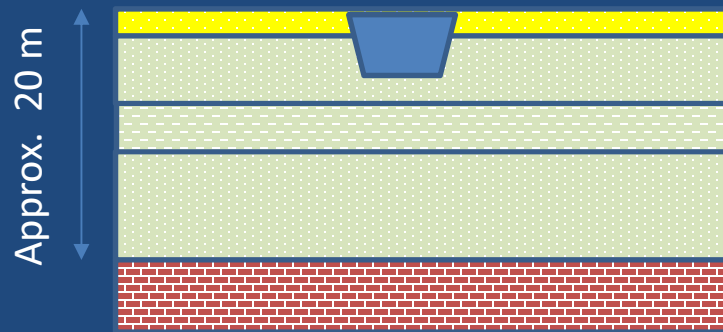
1 Transmissivity (m²/day)





2 Hydraulic Conductivity (m/day)

3 Aquifer Storativity (dimensionless) (not assessed where no monitoring bore data are available)

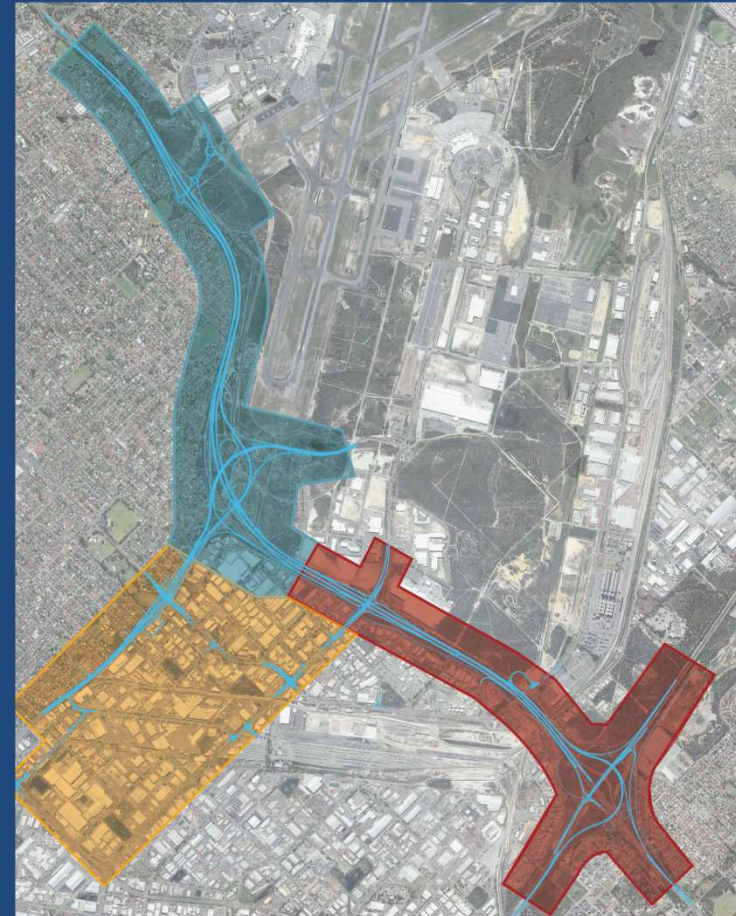
4 All includes both the mineralised and non mineralised Marra Mamba. However, the bore may not screen the entire non-mineralised sequence.

Case study 3 – Gateway WA Pump testing for dewatering



-  Bassendean Sands
-  Guilford Clays
-  Guilford Sands
-  Limestone and carbonate gravels (Mirrabooka Aquifer)

- 2-3 m drawdown for some sites
- High yielding aquifer at 20 m bgl
- Up to 6 months of dewatering is required

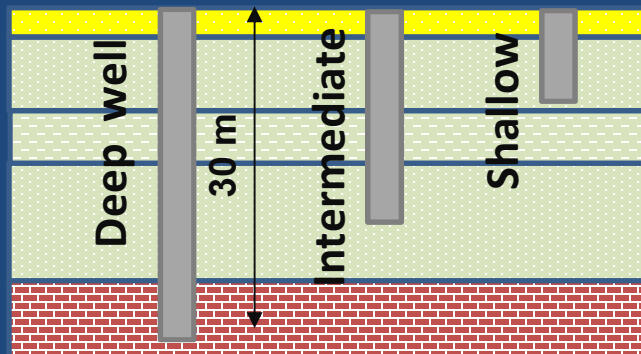
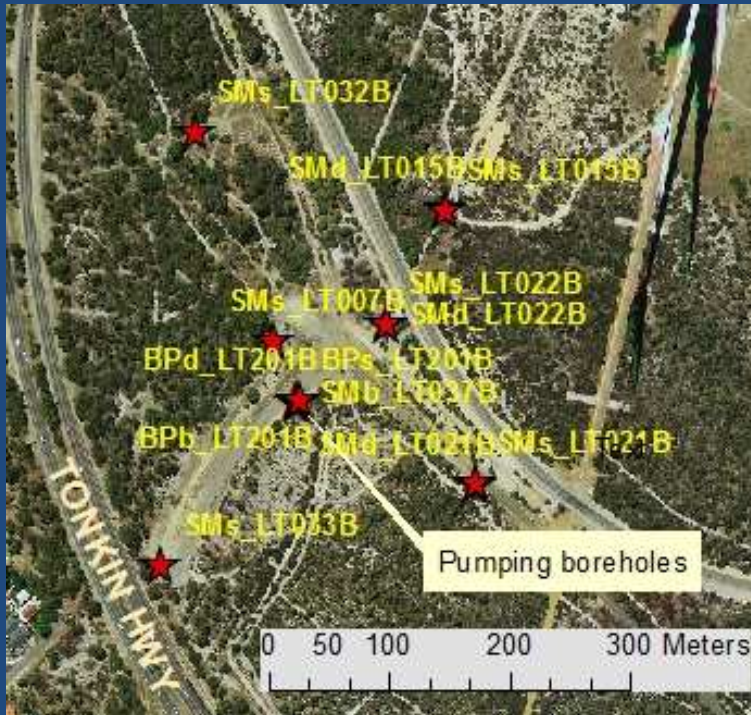


We acknowledge MRWA for opportunity to conduct this study and present the results



Case study 3 – Gateway WA

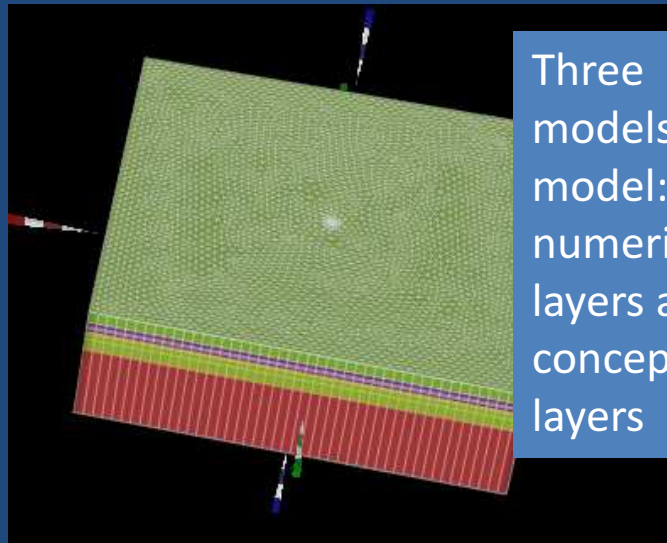
Pump test settings



- Three pumping wells – shallow (10.5 mbgl), intermediate (15.5 mbgl) and deep (30 mbgl);
- Average pumping rates: 6 L/s (deep), 3 L/s (intermediate) and 1.3 L/s (shallow);
- 48 hour pump tests + recovery;
- 11 monitoring wells at distances 2–200 m;
- Screen lengths: 3 m (monitoring wells); 6m, 6m and 12m (pumping wells);
- Screen intervals: all horizons;
- Pressure transducers in all pumping and observation boreholes; digital flowmeters

Case study 3 – original interpretation

FEFLOW model

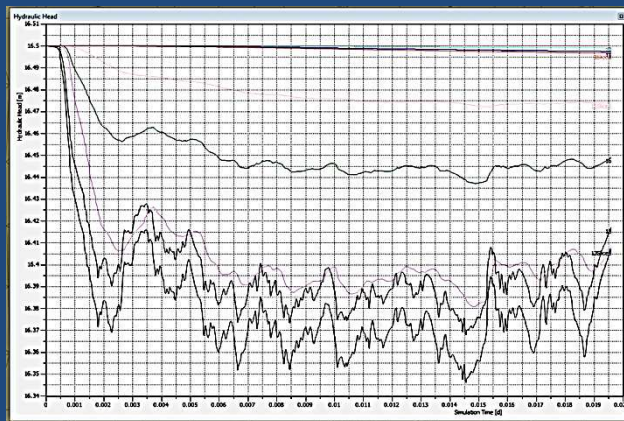


Three models. Each model: 13 numerical layers and 4 conceptual layers

CHALLENGES

- Non-uniqueness
- Requirements for fine vertical discretisation to accommodate various screen and pumping intervals
- Numerical oscillations
- Results are sensitive to numerical parameters (residual water depths, slice location etc.)
- Not sensitive to S_y and K of Mirrabooka
- Sensitivity analysis is subjective

RESULTS

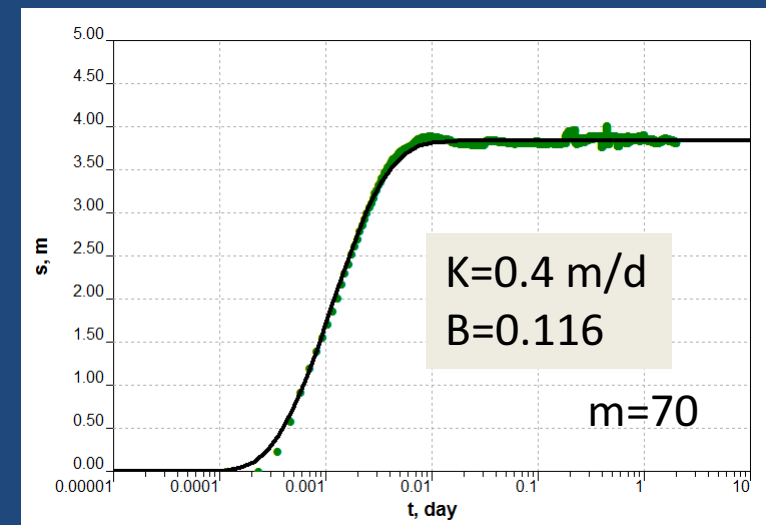
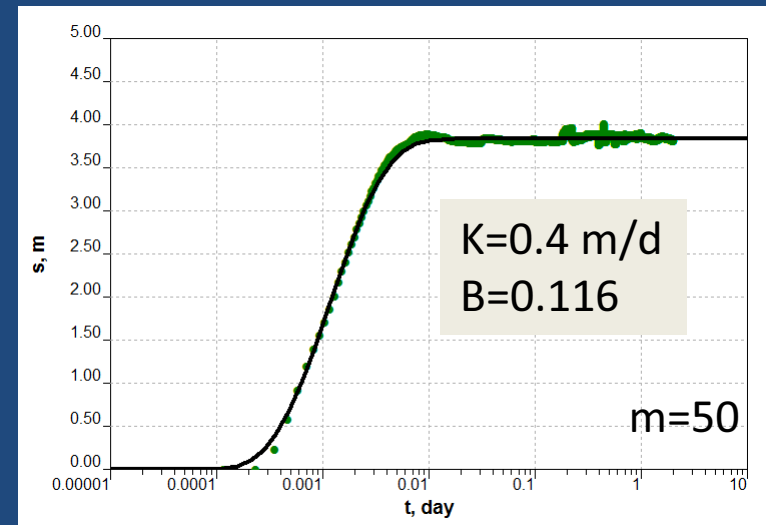
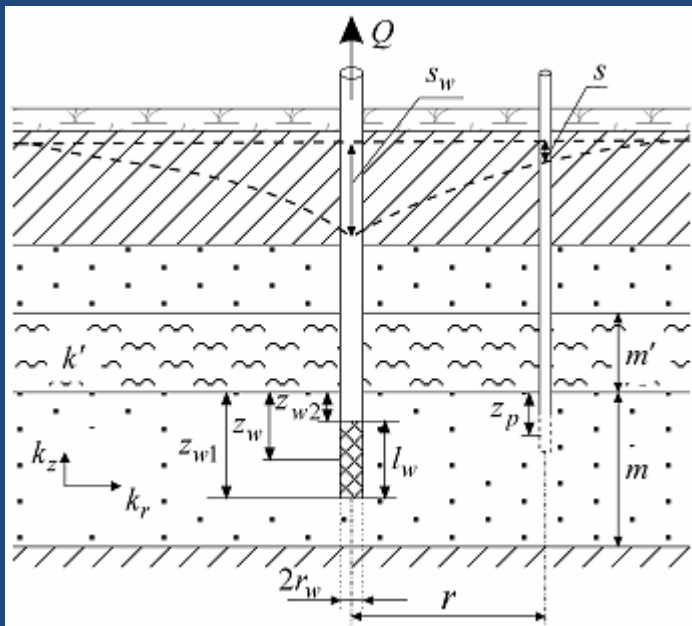


Shallow well: example of oscillations

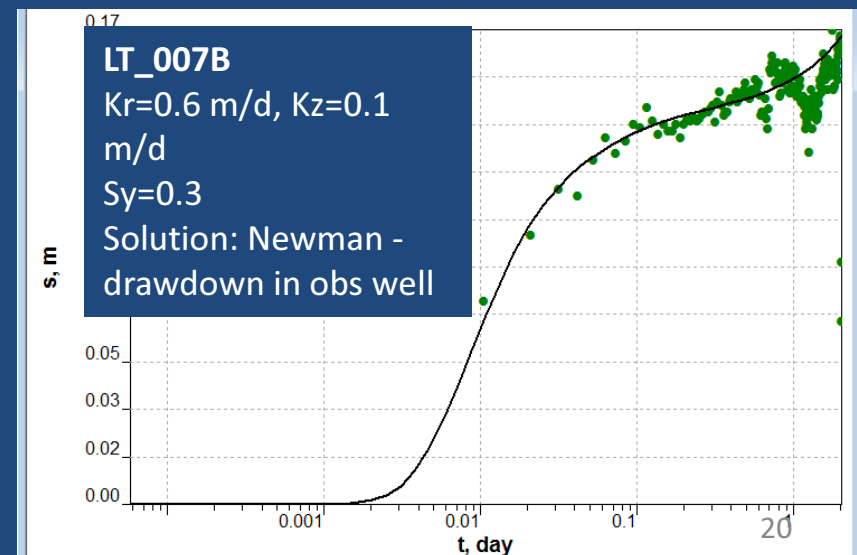
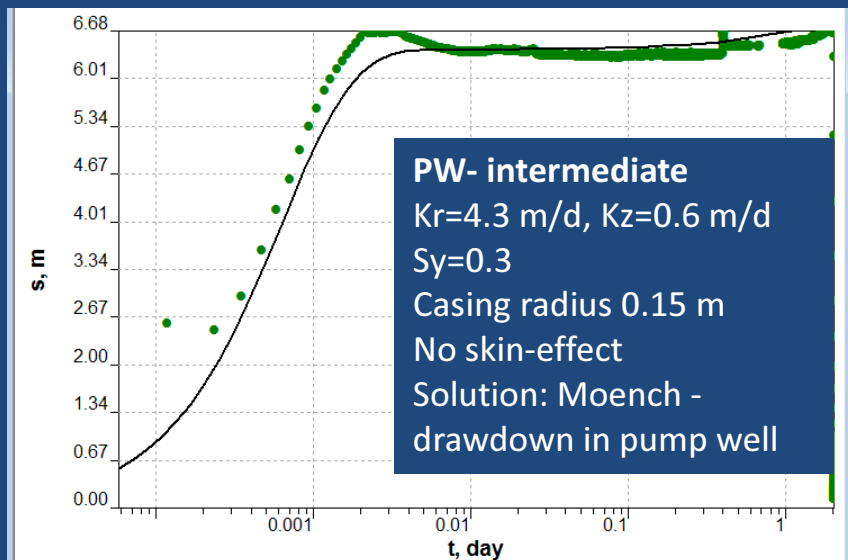
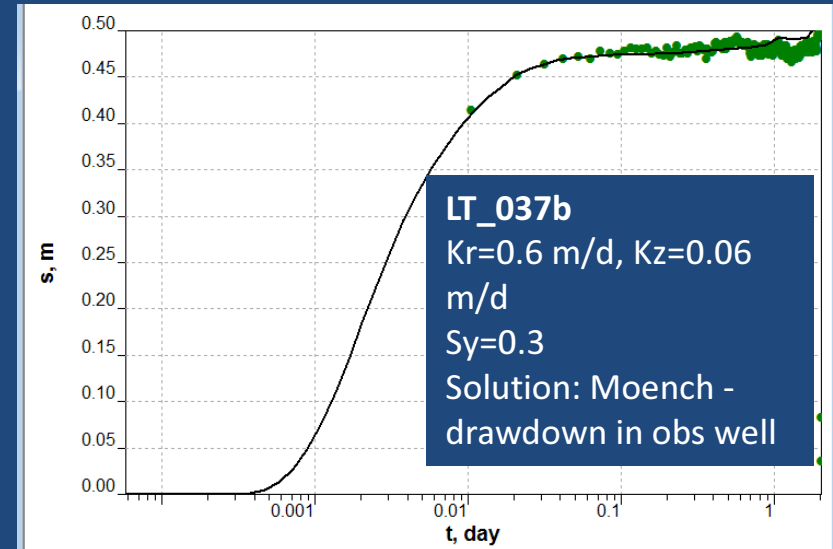
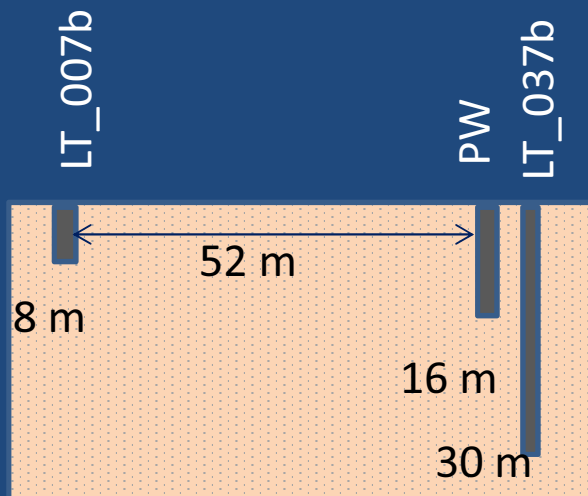
Description	K horizontal		K vertical		Sy range
	Best fit	Acceptable fit	Best fit	Acceptable fit	
Upper sands (Bassendean and GF formations)	7	5-15	1.75	1.8-3.5	0.1-0.3
Sands with silt and clay	1	0.5-1	0.15	0.15-0.3	0.1-0.3
Lower sands of Guildford formation	5.2	5.2-10.4	2	1-4	0.1-0.3
(Mirrabooka Aquifer)	20	15-20	7.5	5-10	0.1-0.3

Case study 3 – corrected interpretation, shallow pumping well

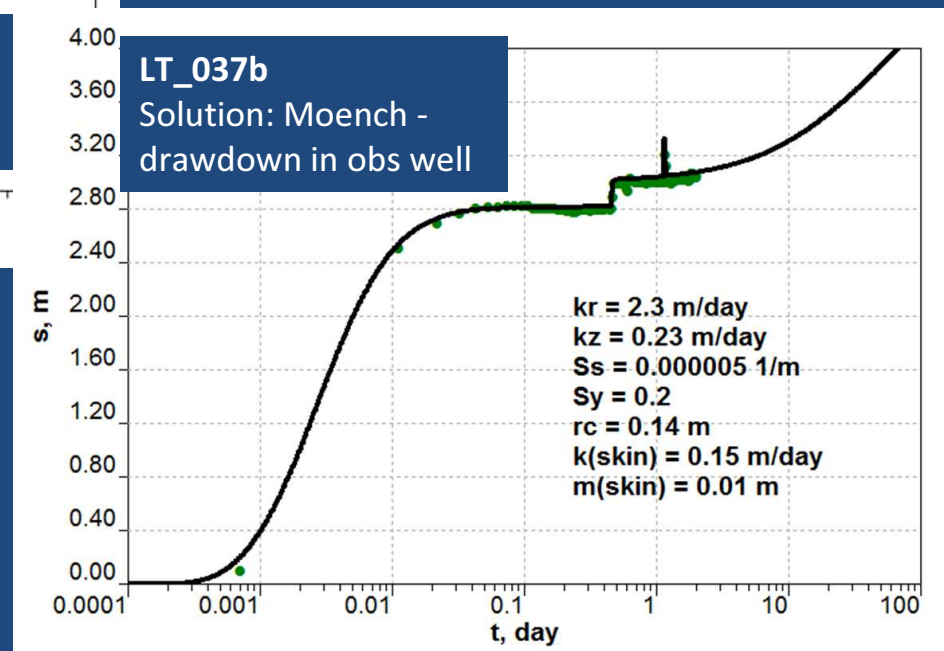
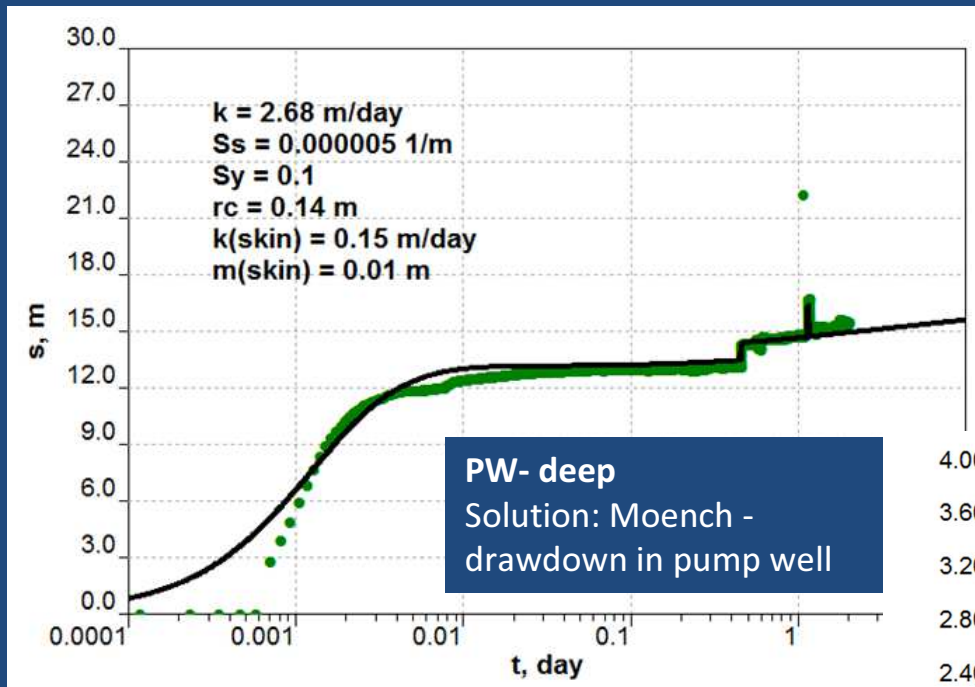
Conceptual scheme
partially penetrating well in an unconfined leaky aquifer
(Hantush solution)



Case study 3 – corrected interpretation, intermediate pumping well



Case study 3 – corrected interpretation, deep pumping well

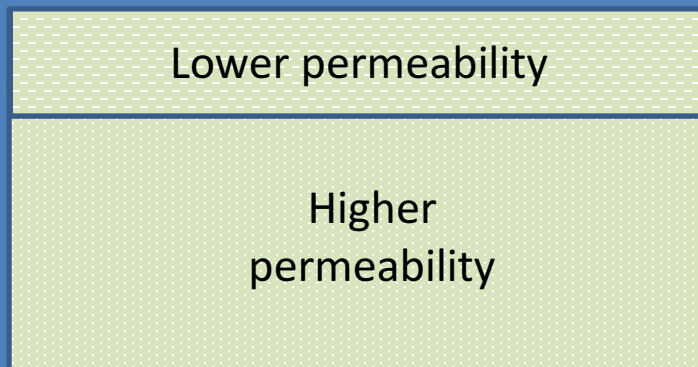


Case study 3 – corrected results and updated profile

Original Results

Description	K horizontal		K vertical		Sy
	Best fit	Acceptable	Best fit	Acceptable	Acceptable
Upper sands (Bassendean and GF formations)	7	5-15	1.75	1.8-3.5	0.1-0.3
Sands with silt and clay	1	0.5-1	0.15	0.15-0.3	0.1-0.3
Lower sands of Guildford formation	5.2	5.2-10.4	2	1-4	0.1-0.3
(Mirrabooka Aquifer)	20	15-20	7.5	5-10	0.1-0.3

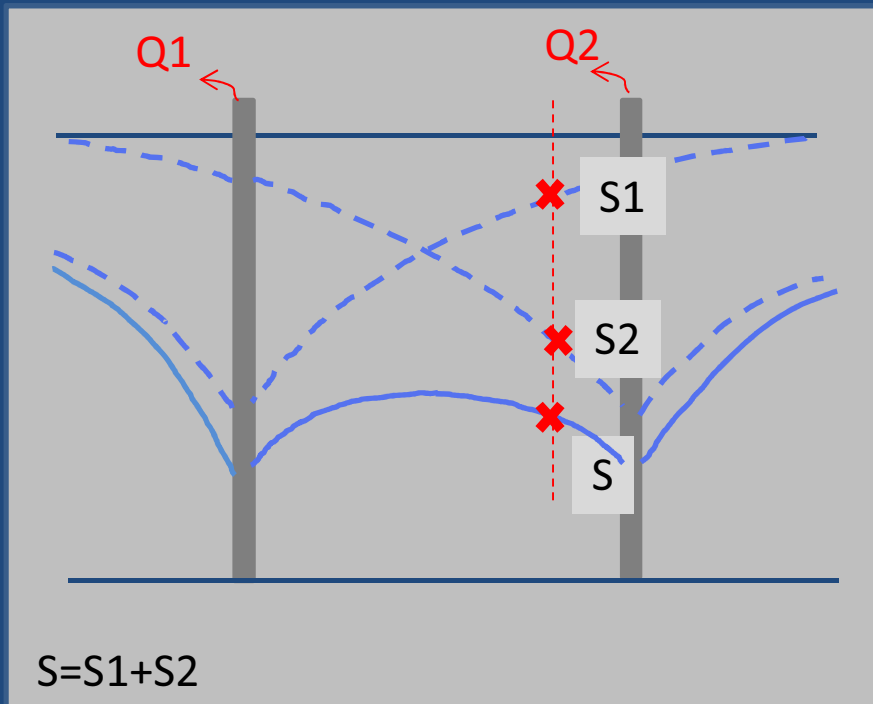
Updated Results



- Upper Sands and Clays – 0.4 m/d
- Lower sands - up to 4 m/d, Sy is between 0.1 and 0.3
- Anisotropy coefficient is up to 10 (not important)
- Mirrabooka aquifer has K similar to that of lower sands

Analytical models for well system design.

Principle of Superposition



Software

- EXCEL,
- EXCEL+ any pump test interpretation software,
- WINFLOW*,
- **AMWELLS**

Standard numerical codes are not modelling drawdown in pumping wells correctly because:

- Grid/element size is not suitable
- Equations for well hydraulics, skin-effect, well and screen diameters etc. are not included

*http://www.scisoftware.com/products/winflow_overview/

Open pit dewatering - wellfield design in EXCEL (gold deposit in CAF)

Superposition formula:

$$s = \frac{1}{T} \sum_{i=1}^n Q_i f_i$$

s – drawdown at any well or at any other point

T – transmissivity;

Q - pumping rate of a single well;

f_i - a function that depends on boundary conditions and well parameters

A linear pit boundary, a linear contour of dewatering wells and a linear contour of recharge at a distance R from a drainage line:

$$f_i = 0.367 \times \lg\left(\frac{R}{r}\right)$$

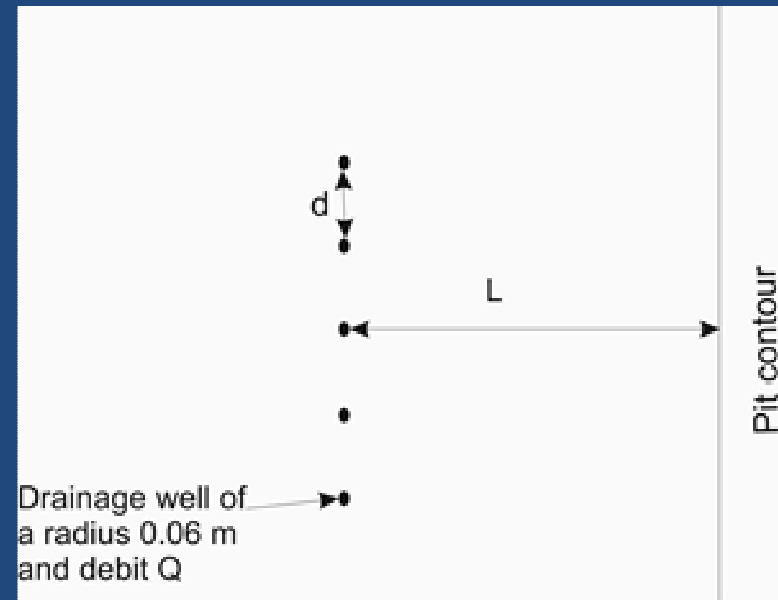
r – distance from a pumping well

R - Radius of Influence

$$R = 1.5 \sqrt{\frac{T \times t}{S}}$$

S – storage coefficient;

t – time from the beginning of pumping

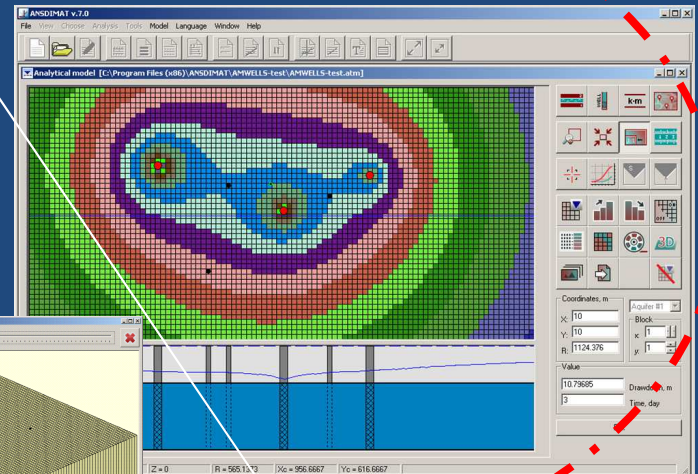
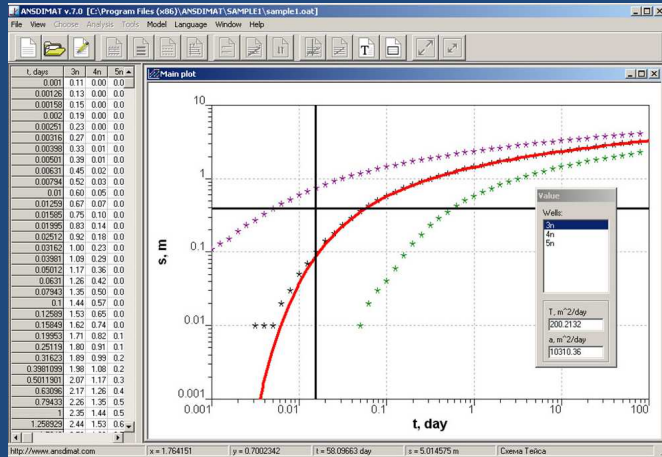


Results: drawdown at a pit contour and inside each well for a specific Q . Helps to decide on number of boreholes and distances between them

ANSDIMAT

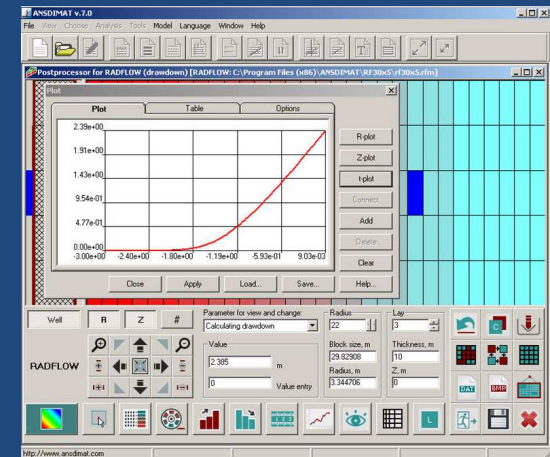
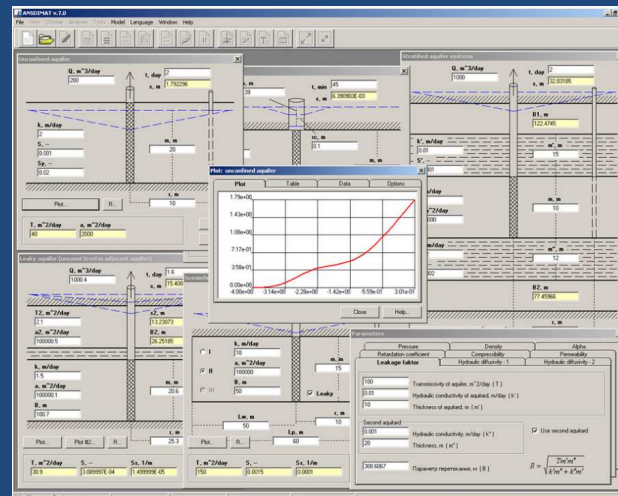
ANSDIMAT

AMWELLS



ANSQUICK

ANSRADIAL



AMWELLS: Model geometry, well locations

The screenshot displays the ANSDIMAT v.8.5 software interface. The main window shows a map of an area with a well location marked by a red dot. The map includes contour lines, roads, and a scale bar. Below the map is a cross-section diagram of the subsurface layers. The software interface includes a menu bar (File, View, Choose, Analysis, Tools, Model, Language, Window, Help) and a toolbar. Several dialog boxes are open:

- Model parameters**: A dialog box with a "Parameters" tab. It lists parameters for hydraulic conductivity and storage coefficient of aquifer and aquitard layers.
- Model**: A dialog box with "Size" and "Boundaries" tabs. It shows model size (2000m x 2000m), coordinate origin (0, 0), and layer thicknesses (18, 5, 25, 10, 30, 88m).
- Recalculation of parameters**: A dialog box showing values for transmissivity, hydraulic diffusivity, specific storage, and leakage factors.

The status bar at the bottom of the main window displays coordinates: X = 1595.302, Y = 15.74808, Z = 37.26471, R = 1030.054, Xc = 917.5, Yc = 800. The URL <http://www.ansdimat.com> is visible at the bottom left.

AMWELLS: Input of well systems – choice of layouts

The screenshot displays the ANSDIMAT v.8.5 software interface. The main window shows an analytical model with a map of a site including features like 'AIRPORT', 'Trister Park', and 'INTERCHANGE'. A 'Create well system' dialog box is open, allowing the user to define well layouts. The dialog includes options for 'Well system' (Line, Rectangle, Parallelogram, Circle) and 'Size of well system' (Number of wells for row, Number of rows, Angle, Length, Width). A 'Variable rate' dialog box is also open, showing a bar chart of pumping rates over time.

Wells and time measurements

Time	Distance
<input type="checkbox"/> 1ws	289.2083 X, m
<input type="checkbox"/> 2ws	452.3925 Y, m
<input type="checkbox"/> 3ws	2500 Rate, m ³ /day
<input type="checkbox"/> 4ws	<input checked="" type="checkbox"/> Variable rate...
<input type="checkbox"/> 5ws	15 Z, m
<input type="checkbox"/> 6ws	30 Length screen, m
<input type="checkbox"/> 7ws	0.1 Well radius, m
<input type="checkbox"/> 8ws	<input type="checkbox"/> Transparent
<input type="checkbox"/> 9ws	Color:
<input type="checkbox"/> 10ws	Random color

Create well system

Well system: Line, Rectangle, Parallelogram, Circle

Size of well system:

- Number of wells for row: 5
- Number of rows: 2
- Angle, degree: 25
- Length, m: 400
- Width, m: 100

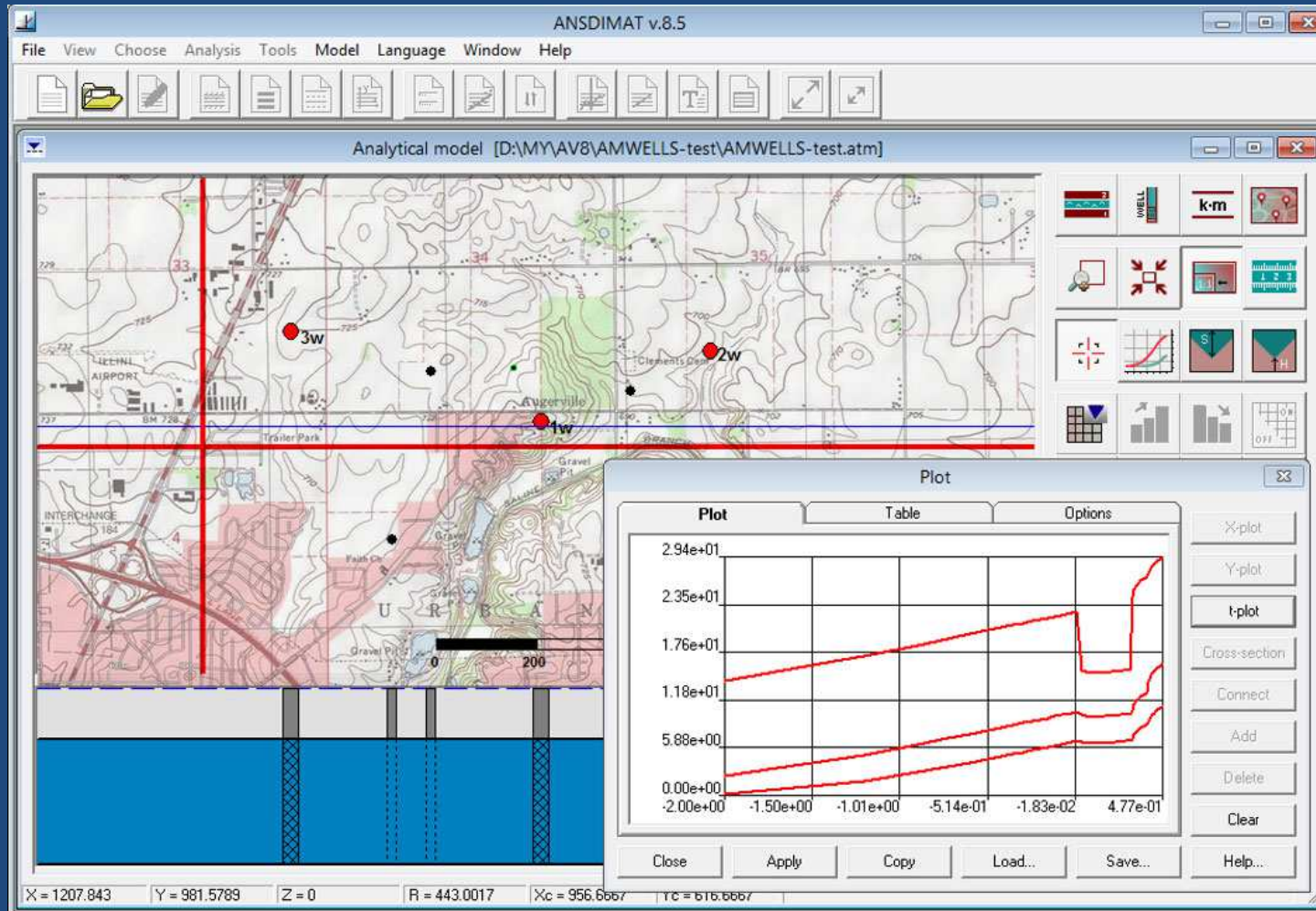
Center, m: X=250, Y=250

Wells: Append, Clear and create

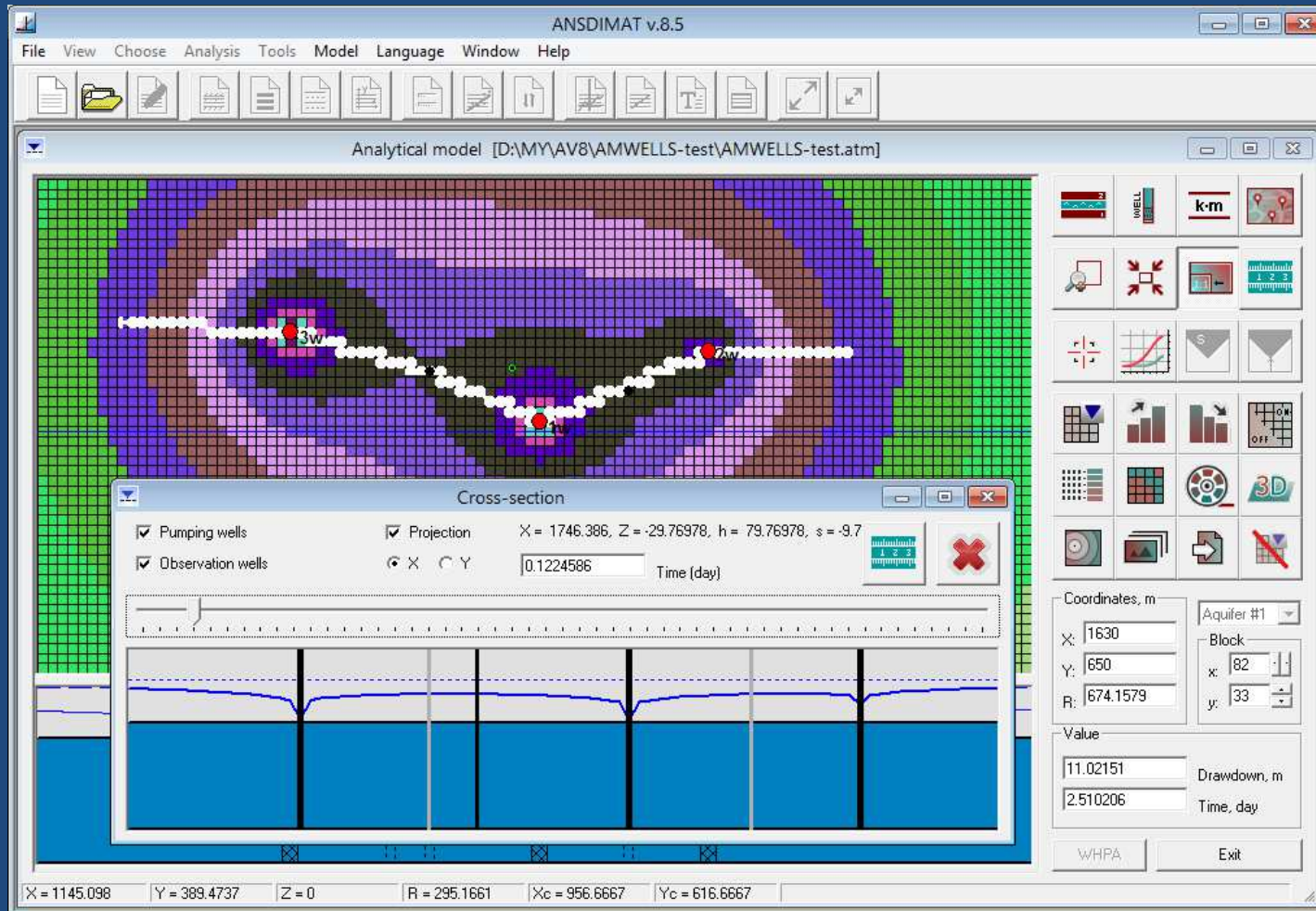
Variable rate

Time (m)	Rate (m ³ /day)
0.00e+00	0.00e+00
2.00e+00	3.60e+02
4.00e+00	7.20e+02
6.00e+00	1.44e+03
8.00e+00	1.08e+03
1.00e+01	7.20e+02

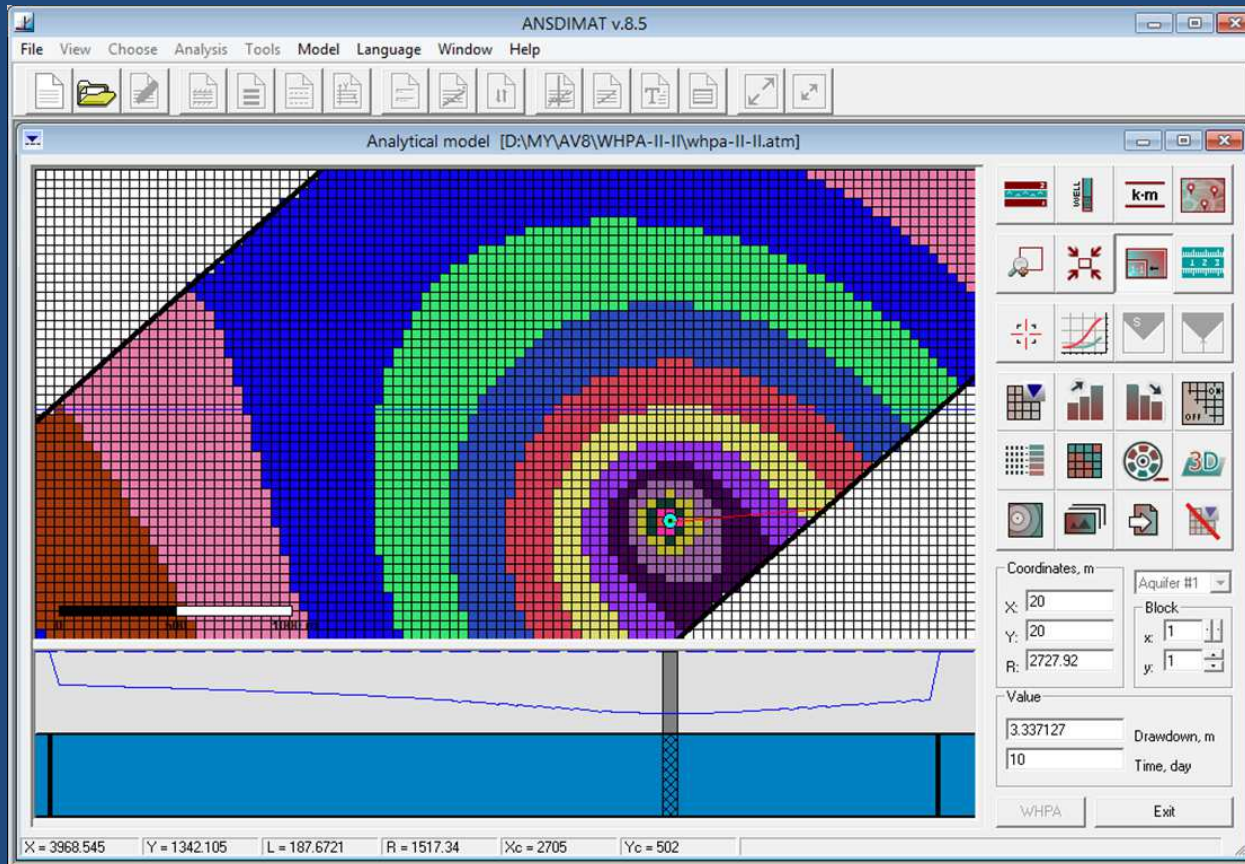
AMWELLS: Calculation of drawdown in each well



AMWELLS: Piezometric maps and hydrogeological cross-sections

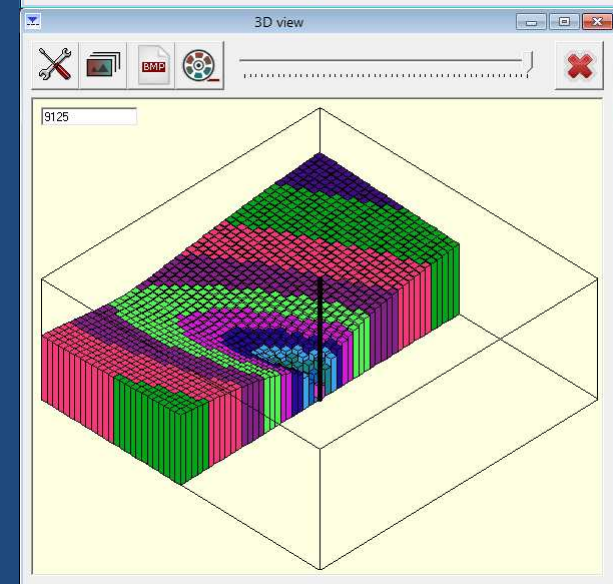
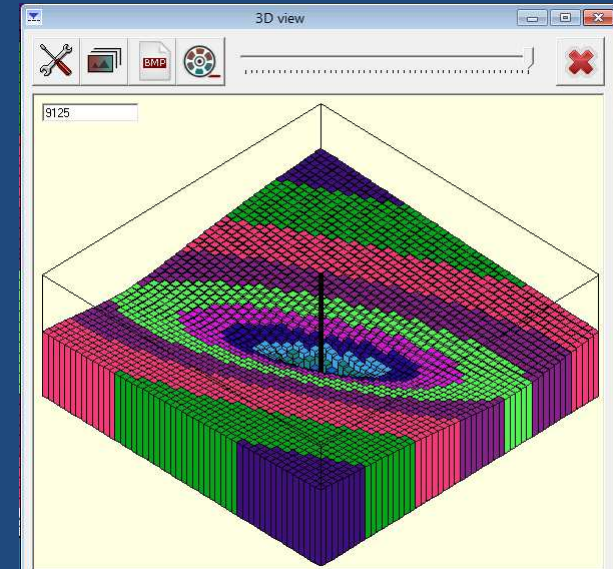
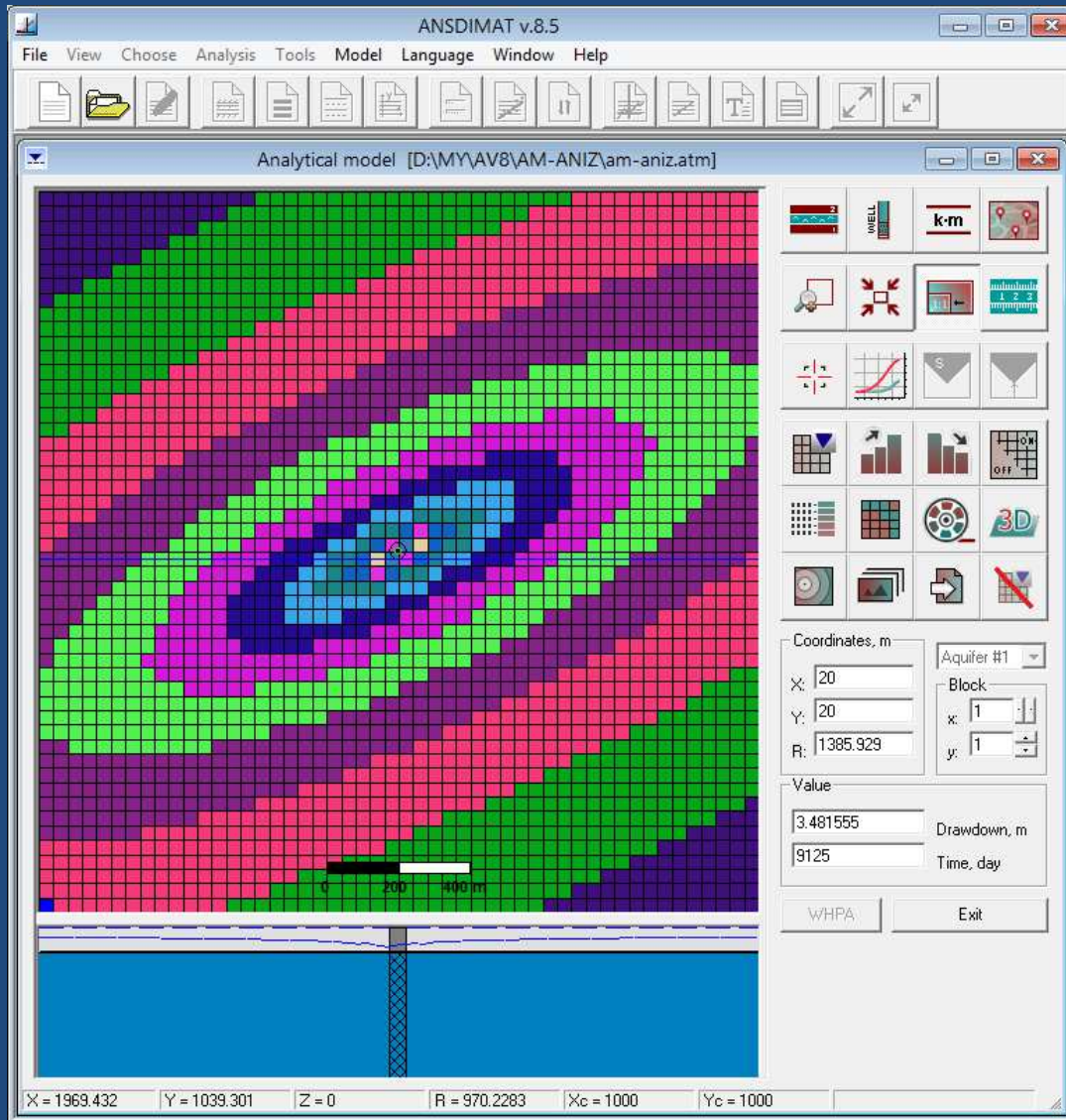


AMWELLS: Hydrodynamic boundaries

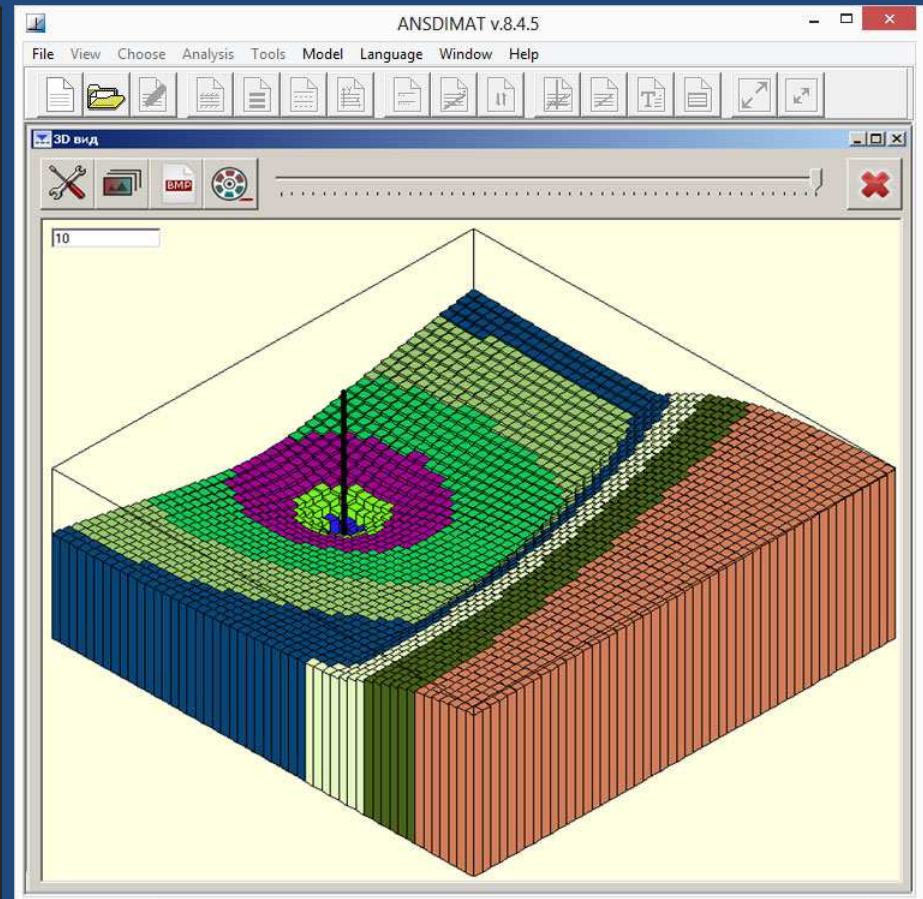
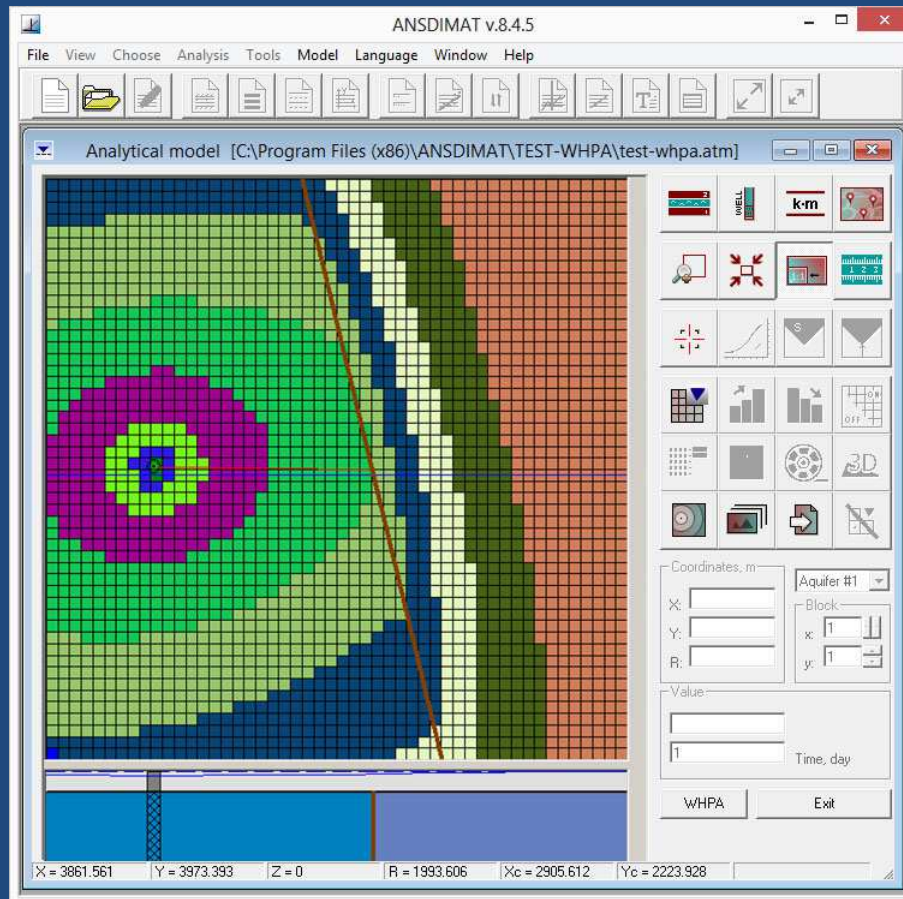


Choice of Dirichlet, Neumann or Cauchy boundaries
(straight line boundaries only)

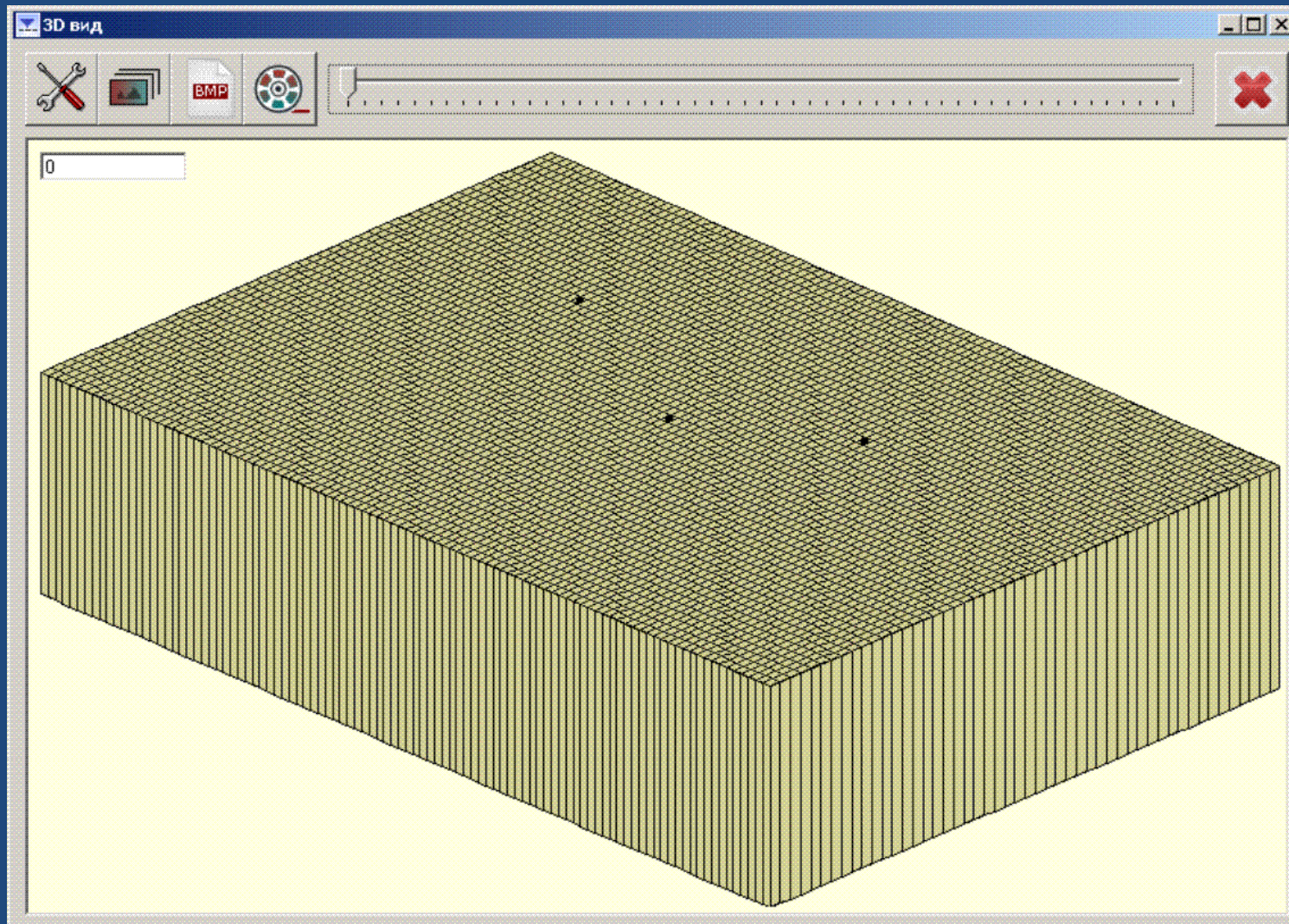
AMWELLS: Anisotropy



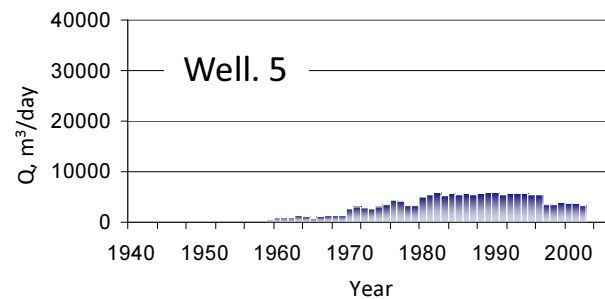
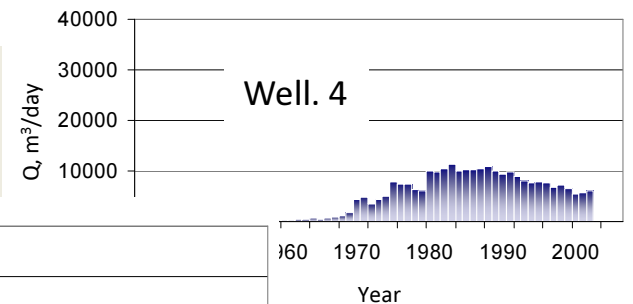
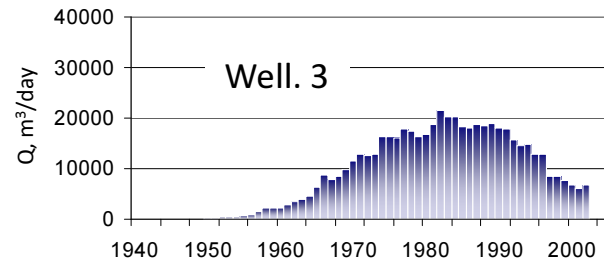
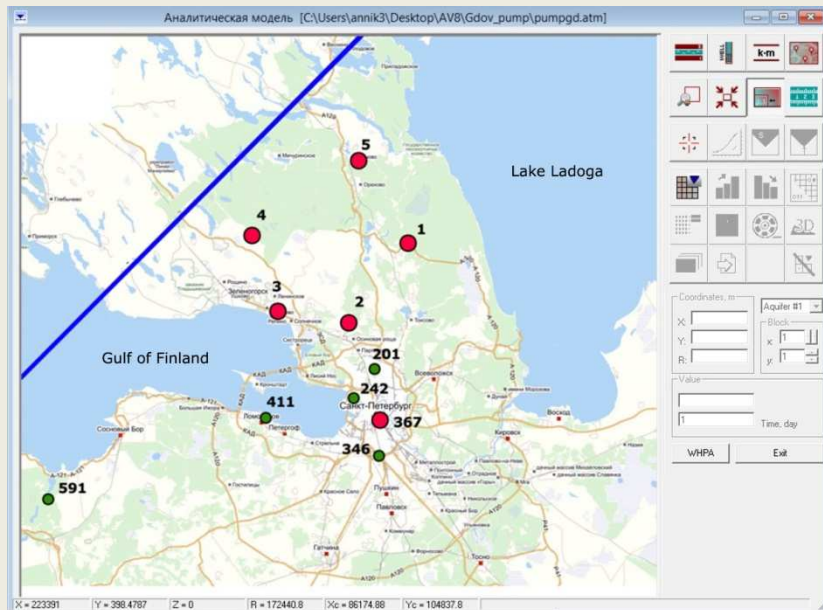
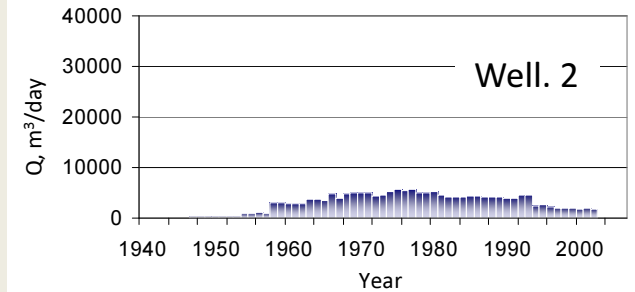
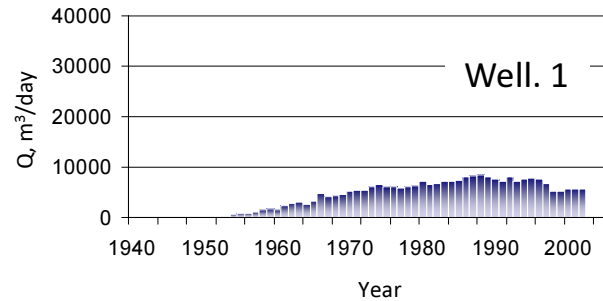
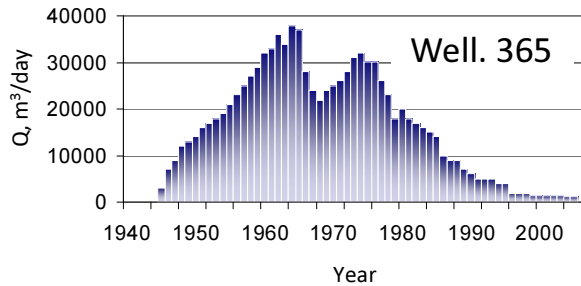
AMWELLS: Heterogeneity



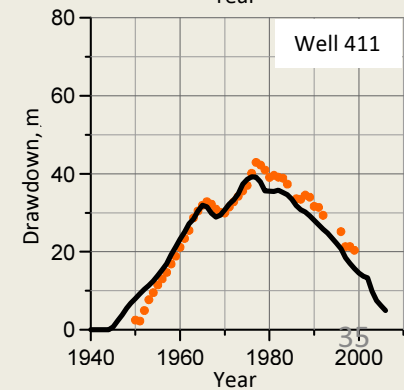
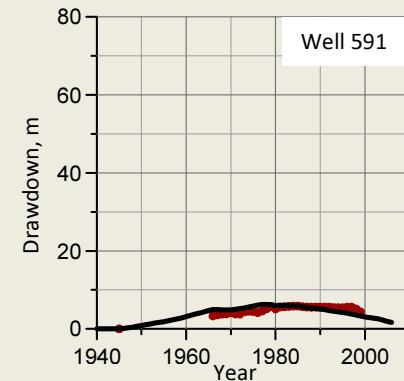
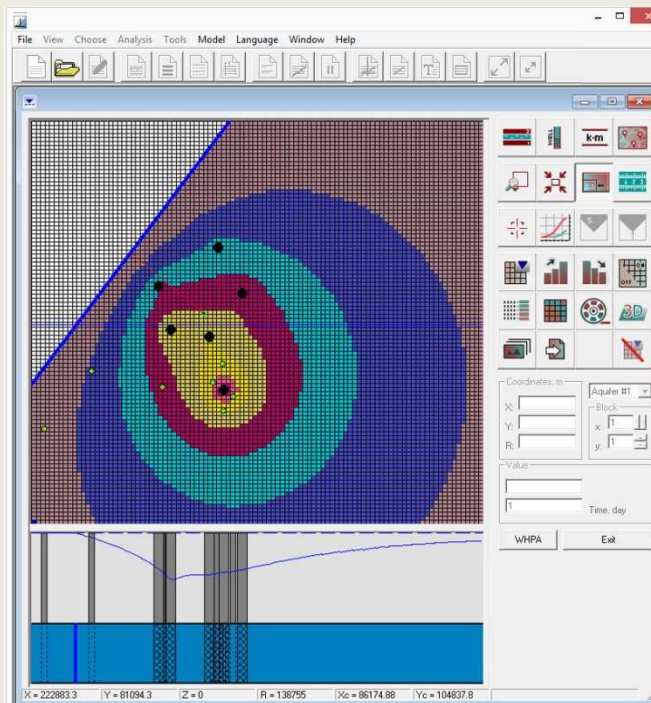
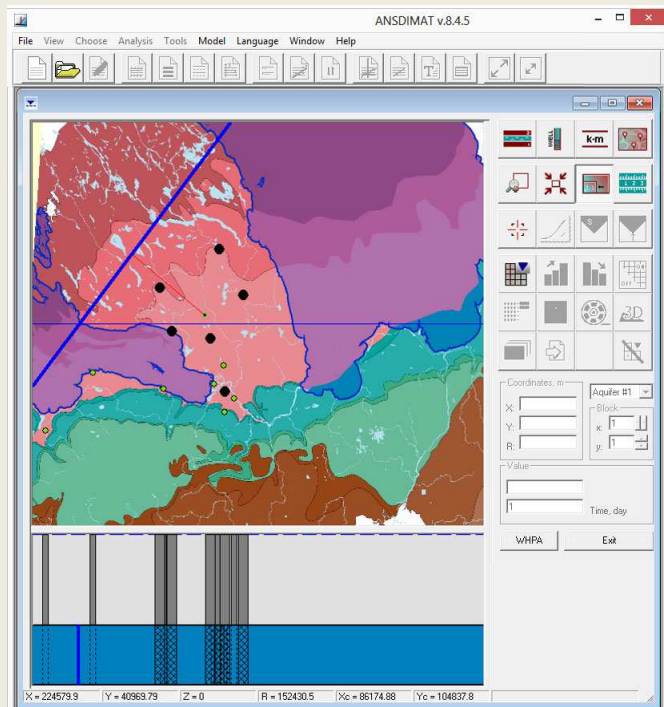
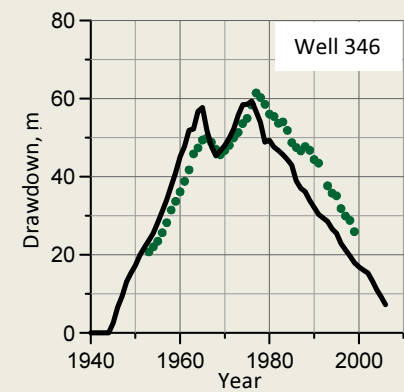
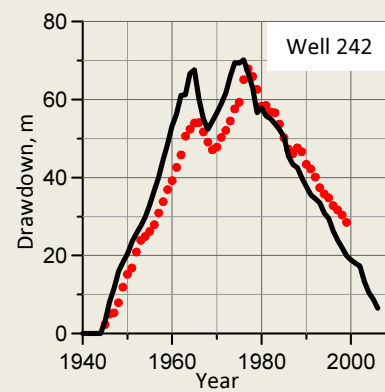
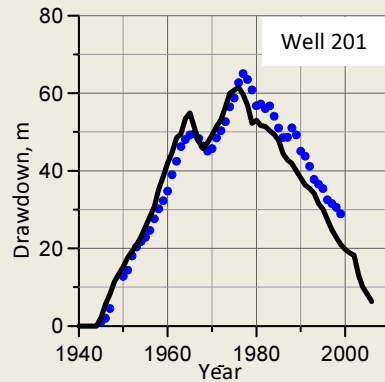
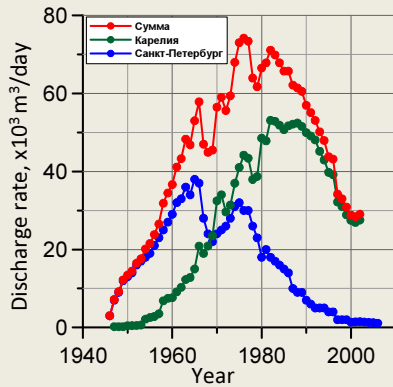
AMWELLS: 3D animation movie



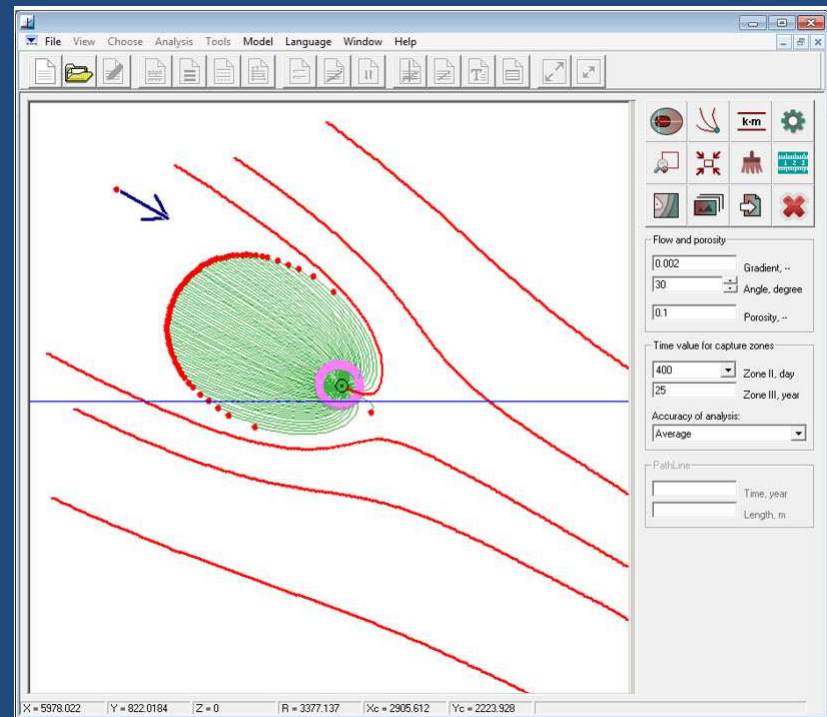
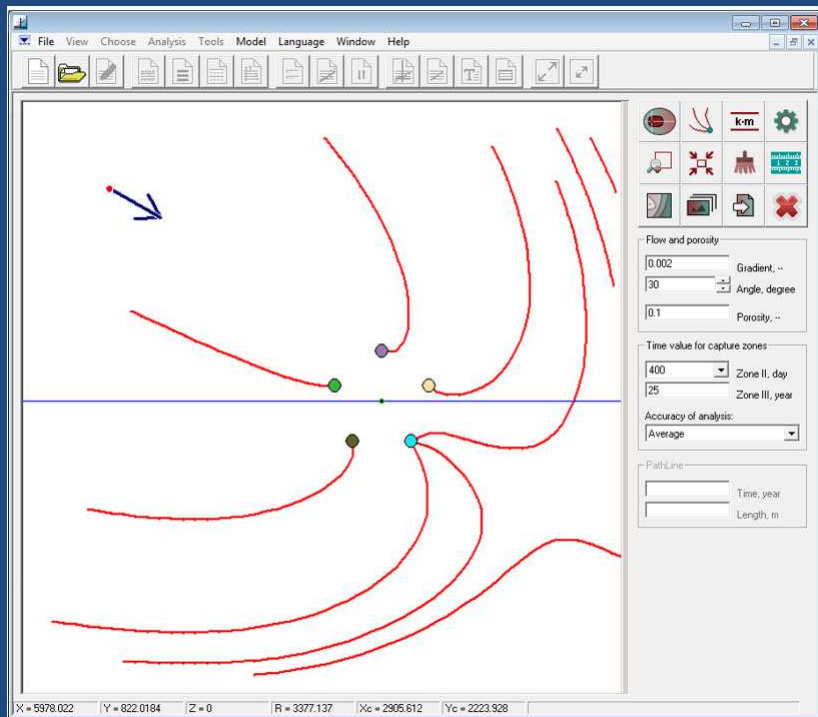
Case study 4: Water supply borefield Leningrad – St-Petersburg, 1946–2006



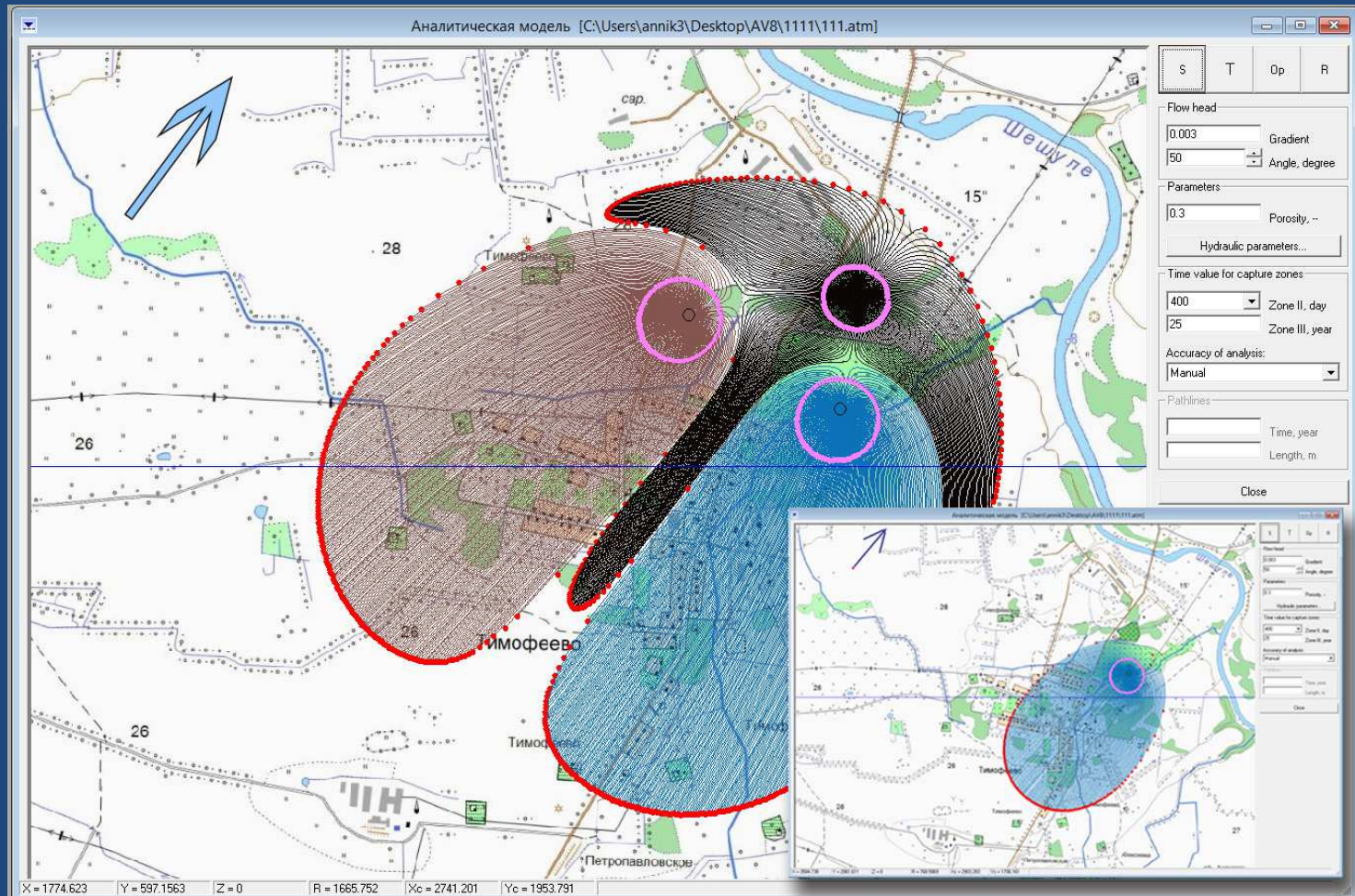
Case study 4: model calibration and predicted drawdowns, 1946–2006



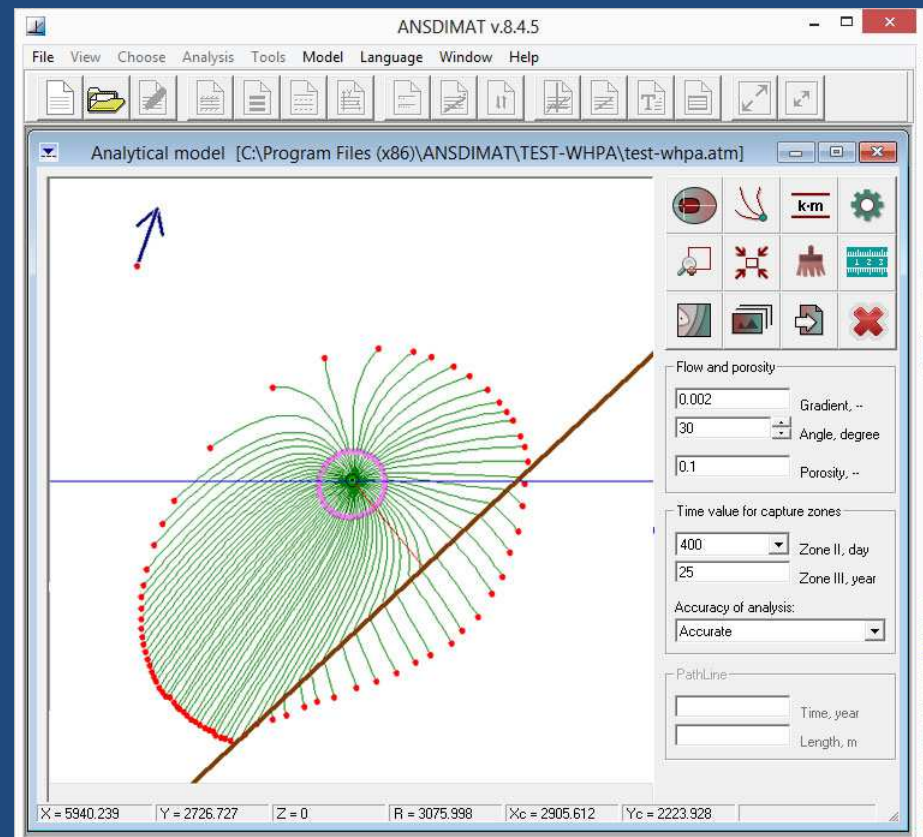
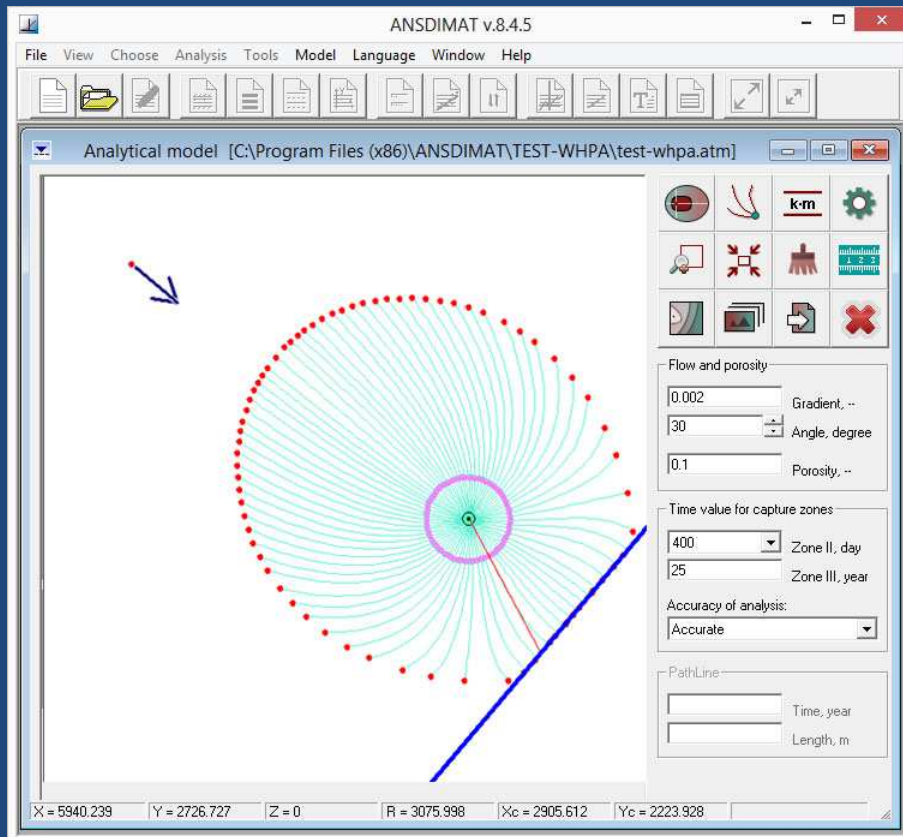
Particle tracking



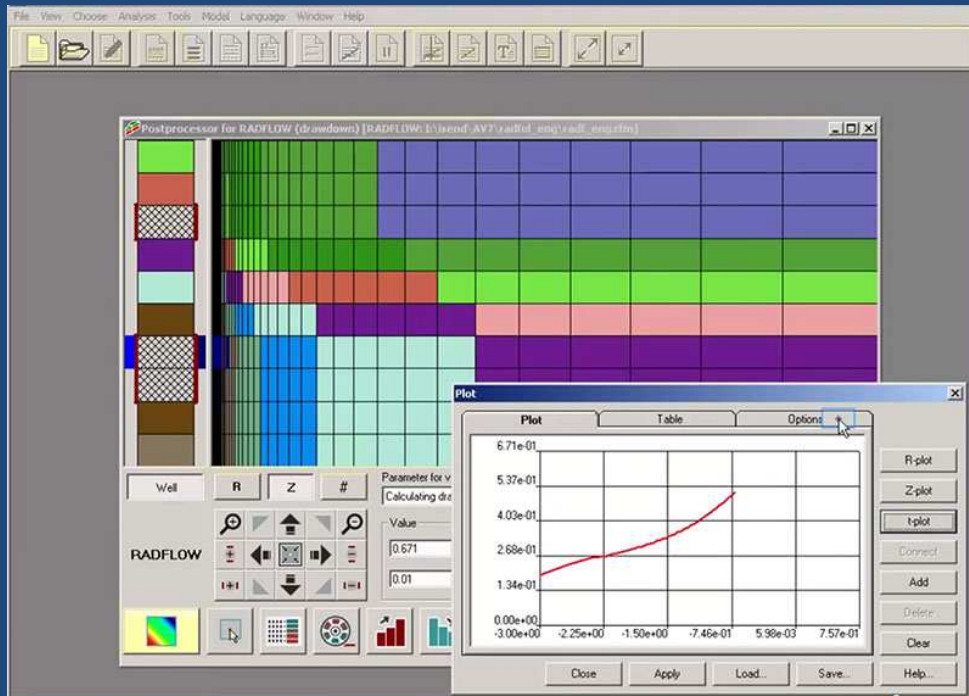
Well catchments (wellhead protection areas)



Impact of boundaries and heterogeneity on well catchments



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...when hydrogeological conditions are too complex to be modelled analytically.

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- MODFE (USGS)
- RADFLOW (G.S. Johnson, D.M. Cosgrove, Idaho Water Resources Research Institute).

Thank you for attention!

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