PetroleumSolutions.co.uk

Waterdrive Help

Waterdrive

Petroleum Reservoir Waterdrive Analysis Software

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by Petroleum Solutions Ltd

Waterdrive Help

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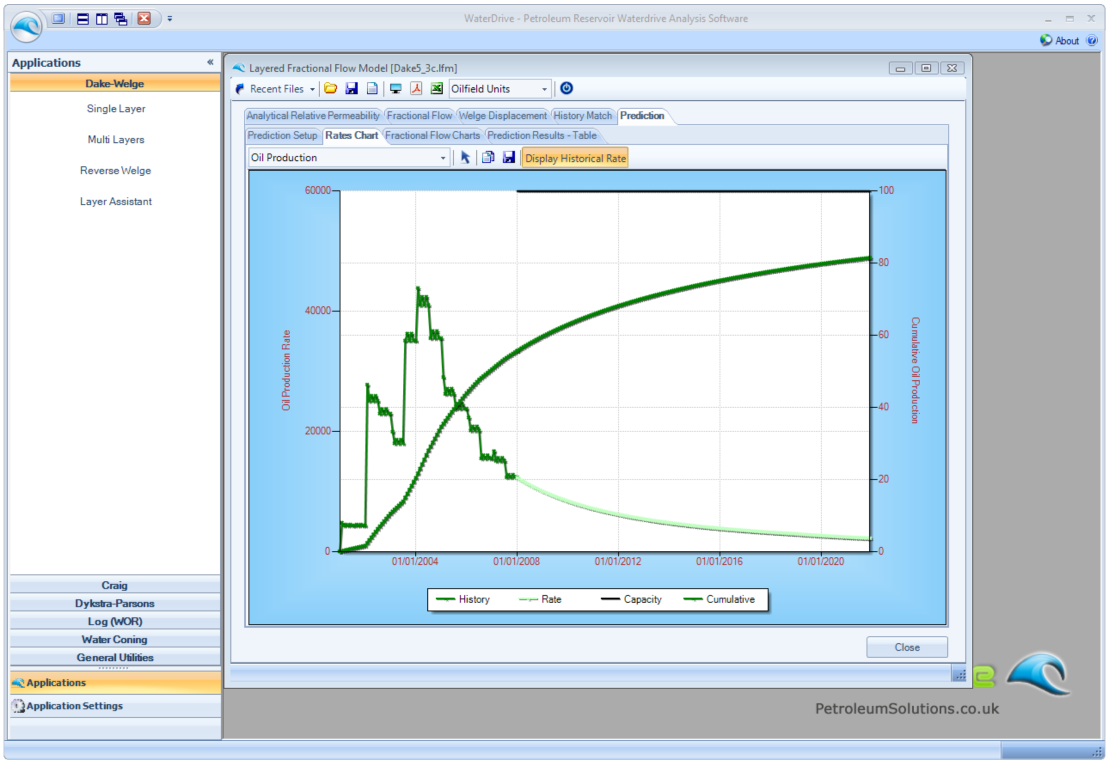
Part I

1 Welcome to Waterdrive

1.1 Introduction



Waterdrive is a collection of classical Waterdrive calculations and routines intended for Petroleum Reservoir Engineers to :

- Analyse the water-oil displacement processes for both homogeneous single layer and heterogeneous multi-layered systems, and permit the calculation of waterflood performance with time for oil recovery, producing watercut and water injection.
- Examine and interpret the waterdrive performance of reservoirs, or numerical simulation models, from an inspection of their production & injection history, by solving Welge's equation in reverse.
- Calculate the waterflood performance with time for a five-spot pattern, using the approach of Craig, Geffen, and Morse for relating oil recovery and producing water-oil ratio (WOR) to cumulative injected water
- Calculate Dykstra-Parsons and Lorenz Heterogeneity coefficients
- Calculate the waterflood performance with time, using two approaches based on the original work of Dykstra-Parsons, which also relates oil recovery and producing water-oil ratio (WOR) to cumulative injected water.
- For water coning in vertical and horizontal wells, determine the critical flow rate,

breakthrough time predictions and performance calculations after breakthrough.

Numerous other smaller routines, or general utilities, are provided to allow efficient calculation of mobility ratio, displacement efficiencies, areal sweep, various conversion utilities and fitting Corey curves to relative permeability data.

License.dat File

The "License.dat" file is located in the Application Startup folder (eg C:\Program Files\Petroleum Solutions\Waterdrive\)

The contents of this ASCII license file needs to contain the following license information.

[License Settings]
LicensedTO =
Company =
ProductID =
LicenseID =

If any of the above License key information is incorrect or absent, or if the License.dat file is missing then the application will fail to startup.

.NET Framework

The Profile application requires the presence or installation of Microsoft .Net Framework version 2.

.NET Framework version 2 is a component of the Microsoft Windows® operating system used to build and run Windows-based applications.

Should .NET Framework version 2 not be installed on the destination PC then a link is provided below to download this system software. The user should download and install .NET Framework version 2 before attempting to install Waterdrive.

http://www.petroleumsolutions.co.uk/downloads.html

The installation of .Net Framework also requires a minimum software and hardware requirement. Details of which are shown below. Specifically, note that you cannot install the .NET Framework on a computer running the Microsoft Windows 95 operating system.

Minimum requirements

To install .NET Framework [Dotnetfx2.exe], you must have one of the following operating systems, with Microsoft Internet Explorer 5.01 or later installed on your computer:

- Microsoft® Windows® 98
- Microsoft® Windows® 98 Second Edition
- Microsoft® Windows® Millennium Edition (Windows Me)
- Microsoft® Windows NT® 4 (Workstation or Server) with Service Pack 6a
- Microsoft® Windows® 2000 (Professional, Server, or Advanced Server) with the latest Windows

service pack and critical updates available from the Microsoft Security Web site (www.microsoft.com/security).

- Microsoft® Windows® XP (Home or Professional)

Recommended hardware

CPU Recommended	RAM Recommended
Pentium 90 MHz or faster	96 MB or higher

Part II

2 Dake-Welge

Immiscible Displacement in Porous Media

The analysis and description of the immiscible displacement process by analytical methods are still of fundamental importance for the prediction of reservoir behaviour, despite the ready availability of numerical modelling methods.

Before any numerical simulation study an engineer should analyse, by non-numerical means, the displacement processes that are considered likely in the reservoir.

In Chapter 5 Waterdrive of Dake's "The Practice of Reservoir Engineering", he highlights the need to caution in applying core flooding experiments directly in numerical simulation studies and the dangers of conducting these simulation studies in isolation of parallel analytical calculations. An extract from chapter 5 is given below, in which he states :

"There are three levels on which the phenomenon of water-oil displacement can be viewed:
- *the electron microscope scale (EMS)*
- *the microscopic, one-dimensional scale of a core flooding experiment*
- *flooding in hillsides......which is the reality of practical reservoir engineering*

.....The perennial difficulty in the description of waterdrive has always been how to relate the core flooding results, which are little affected by such complications as heterogeneity and gravity, to the hillside in which these same factors are usually dominant. The scaling-up of laboratory results for use in a meaningful fashion in field studies is one of the main topics in this and subsequent sections and particularly the sensitive matter of how the results of relative permeability experiments are input to numerical simulation models in such a way as to honour the basic laws of physics."

Reservoirs are, of course, three-dimensional.

However, reservoir thickness is almost always much smaller than the areal dimensions. Therefore, the study of displacement processes can be reduced to a two-dimensional heterogeneous (layered) problem, with the reservoir divided into vertical slices in the x-z, or y-z, plane. These routines are implemented and discussed further in the Multi Layer Fractional Flow Model section. Also, if the reservoir layer thickness is small, and is less than the capillary transition zone between oil and water, the system can further be reduced to a one dimensional homogeneous linear problem. These routines are discussed further in the Single Layer Fractional Flow Model section.

The basic assumptions made when attempting to describe the displacement processes are :

- Oil and water are the only mobile fluids in the porous medium, and move in the same direction.
- Water is displacing oil in a water wet reservoir, such that the displacement is an imbibition process, and the movement of the two fluids is described by their relative permeability curves.
- The displacement is considered as incompressible. This assumption implies that steady state conditions prevail in the reservoir with the pressure at any point remaining constant.
- The displacement is considered to be linear.

Laurie Dake's - The Practice of Reservoir Engineering

Laurie Dake's two textbooks, namely :

"Fundamentals of Reservoir Engineering", Elsevier, 1978-1985
"The Practice of Reservoir Engineering", Elsevier, 1994-2001

are probably the most referenced technical manuals within the discipline of Reservoir Engineering.

Perhaps the most fitting tribute to these books can be found on amazon.com from Malcolm Pye, of the UK's Department of Trade and Industry.

"...This book tells you all you need to know about reservoir engineering.

Chapter 5 is Laurie's masterpiece, 150 pages on waterdrive which could be published as a book in its own right. Drawing on examples from the North Sea, the biggest laboratory ever for the study of waterdrive it demolishes the misconceptions that have grown up over relative permeability curves and stresses the importance of the fractional flow equation in understanding fluid displacement. "

The techniques, presented within these two books, form the basis for the routines contained within this section.

References:

Dake, L., "*Fundamentals of Reservoir Engineering",* Elsevier Scientific Publishing Company, 1978.

Dake, L., *"The Practice of Reservoir Engineering",* Elsevier Scientific Publishing Company, 1994.

2.1 Single Layer Fractional Flow Model

Diffuse flow means that the viscous, or dynamic, forces are more dominant than the gravity forces, so that vertical variation in saturations may be neglected. Typical characteristics for this type of flow condition are low vertical permeability, combined with a high horizontal pressure gradient.

The converse to diffuse flow condition is the more common condition of segregated flow. Segregated flow is where the gravity forces are more dominant than the the viscous, or dynamic, forces, so that vertical variations in saturations are significant. Typical characteristics for this type of flow condition are high vertical permeability, combined with a low horizontal pressure gradient.

Both of the above flow conditions are implemented within this routine, and are discussed in more detail in the following sections

2.1.1 Diffuse Flow Condition

The diffuse flow condition can be encountered under two extreme physical conditions:

a. when displacement occurs at very high injection rates so that the condition of vertical equilibrium is not satisfied and the effects of capillary and gravity forces are negligible, and
b. for displacement at low injection rates in reservoirs for which the measured capillary transition zone greatly exceeds the reservoir thickness and the vertical equilibrium condition applies.

Diffuse flow is where the fluid saturations at any point in the linear displacement path are uniformly distributed with respect to thickness. The sole reason for making this assumption is that it permits the displacement to be described, mathematically, in one dimension and this provides the simplest possible model of the displacement process.

The following describes the method and physics governing diffuse flow displacement through a linear homogeneous cross section of a reservoir, as outlined by Dake[1].

1. Calculate the fractional flow curve, from the following equation, allowing for gravity effects but neglecting capillary pressure.

$$f_w = \frac{1 - \frac{k.k_{ro}.A}{q_t.\mu_o} \cdot \frac{\Delta\rho.g.\sin\theta}{1.0133x10^6}}{1 + \frac{\mu_w}{k_{rw}} \cdot \frac{k_{ro}}{\mu_o}}$$

2. Calculate the tangent to the fractional flow curve, from the point Sw = Swc & fw = 0. The point of tangency has the coordinates Sw=Swbt & fw=fwbt, and the extrapolation of this line to fw=1 gives the value of the average saturation behind the front at breakthrough.

The following equations can be applied to calculate the oil recovery and time at which breakthrough occurs.

$$N_{pd_{bt}} = W_{id_{bt}} = q_{id}.t_{bt} = \left(\overline{\overline{S}}_{w\,bt} - S_{wc}\right) = \frac{1}{\left.\frac{df_w}{dS_w}\right|_{S_{wbt}}}$$

$$t_{bt} = \frac{W_{id_{bt}}}{q_{id}}$$

3. Applying the following equation to all Sw values greater than Swbt, with coordinate values of Swe & fwe, will result in the average water saturation in the reservoir block.

$$\overline{\overline{S}}_w = S_{we} + \left(1 - f_{we}\right)\frac{1}{\left.\frac{df_w}{dS_w}\right|_{S_{we}}}$$

4. For each value of Swe, the average water saturation is calculated and the subsequent oil recovery is calculated from the following equation.

$$N_{pd} = \overline{\overline{S}}_w - S_{wc} = \left(S_{we} - S_{wc}\right) + \left(1 - f_{we}\right)W_{id}$$

Wid, the number of pore volumes of water injected, is calculated from the reciprocal of the slope of the fractional flow curve, and is used to attach a time scale to the oil recovery from the following equation.

$$W_{id} = q_{id}.t$$

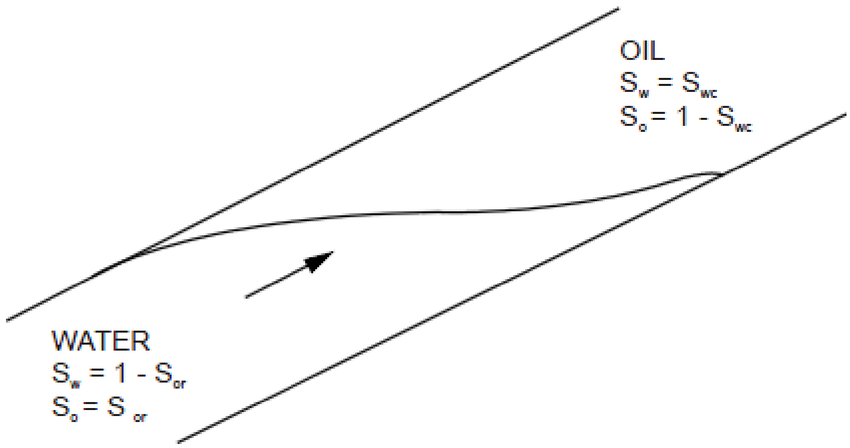
References:

Dake, L., "*Fundamentals of Reservoir Engineering",* Elsevier Scientific Publishing Company, 1978.

2.1.2 Segregated Flow Condition

This is the most common flooding condition encountered in nature and is characterised by the following physical conditions:

- There is a high degree of pressure equilibrium across the reservoir section which encourages cross-flow of fluids under the influence of gravity.
- The displacement occurs under strictly segregated conditions with a sharp interface between the water and oil.



Displacement of oil by water assuming segregated flow conditions

In a segregated flow regime we assume that ahead of the interface between the displacing fluid and the oil, oil alone is flowing, in the presence of immobile water at its irreducible saturation. Behind the interface, only displacing fluid is flowing, in the presence of immobile oil at its residual saturation.

The following describes the method of calculation for segregated flow displacement, as outlined by Dake [1].

Calculate the endpoint mobility ratio, from the following :

$$M = \left(\frac{k'_{rw}}{\mu_w}\right) \Big/ \left(\frac{k'_{ro}}{\mu_o}\right)$$

Calculate the dimensionless gravity number, from the following :

$$G = \frac{4.9 \times 10^{-4} k.k'_{rw}.A.\Delta\gamma.\sin\theta}{q_t.\mu_w}$$

Determine if the displacement condition will be stable or unstable; the displacement will be stable if G > M - 1, and unstable if G < M - 1.

For horizontal reservoirs with no dip and stable displacement, Widbt = 1 / M, Widmax = M and Npd can be calculated, for any value of Wid between Widbt and Widmax, from the following :

$$N_{pD} = \frac{1}{M-1}\left(2\sqrt{W_{iD}M} - W_{iD} - 1\right)$$

For reservoirs with dip, Widbt and Widmax can be calculated from the following :

Stable displacement	$W_{iD_{bt}} = 1 - \frac{h}{2L\tan\beta}$	Widmax = M / (G + 1)
Unstable displacement	Widbt = 1 / (M - G)	Widmax = M / (G + 1)

and Npd can be calculated, for any value of Wid between Widbt and Widmax, from the following :

Stable displacement

$$N_{pD} = 1 - \frac{(h - y_e)^2}{2hL\tan\beta}$$

Unstable displacement

$$N_{pD} = \frac{1}{M-1}\left(2\sqrt{W_{iD}M\left(1 - \frac{G}{M-1}\right)\left(1 - \frac{W_{iD}G}{M-1}\right)} - W_{iD}\left(1 - \frac{M+1}{M-1}G\right) - 1\right)$$

where ye is the height of water at the producing well.

For completeness, the critical rate for by-passing is calculated from the following, and will be stable for dipping reservoirs at 90% of this calculated rate :

$$q_{crit} = \frac{4.9 \times 10^{-4} k.k'_{rw}.A.\Delta\gamma.\sin\theta}{\mu_w(M-1)}$$

2.1.3 Example

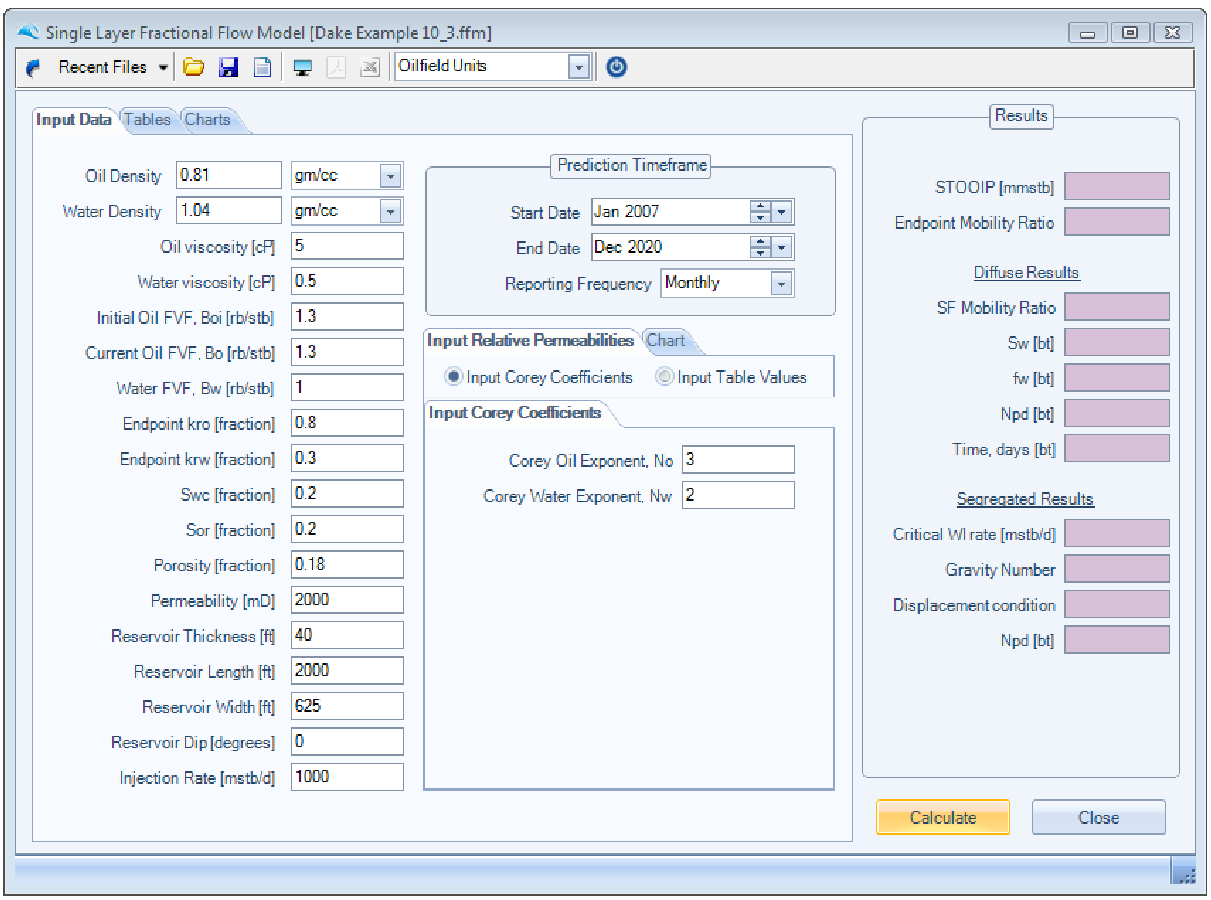
In Chapter 10 Immiscible Displacement of Dake's *"Fundamentals of Reservoir Engineering"*, he provides the following example.

General Input Data	
Oil Density, gm/cc	0.81
Water Density, gm/cc	1.04
Oil viscosity [cP]	5

Water viscosity [cP]	0.5
Initial Oil FVF, Boi [rb/stb]	1.3
Current Oil FVF, Bo [rb/stb]	1.3
Water FVF, Bw [rb/stb]	1
Endpoint kro [fraction]	0.8
Endpoint krw [fraction]	0.3
Swc [fraction]	0.2
Sor [fraction]	0.2
Corey Oil Exponent	3
Corey Water Exponent	2
Porosity [fraction]	0.18
Permeability [mD]	2000
Reservoir Thickness [ft]	40
Reservoir Length [ft]	2000
Reservoir Width [ft]	625
Reservoir Dip [degrees]	0
Injection Rate [mstb/d]	1000

With regards to inputting relative permeability data, the user can choose between using Corey Exponents for Oil and Water curvature or inputting the table values directly. The example below assumes Corey Exponents are input.

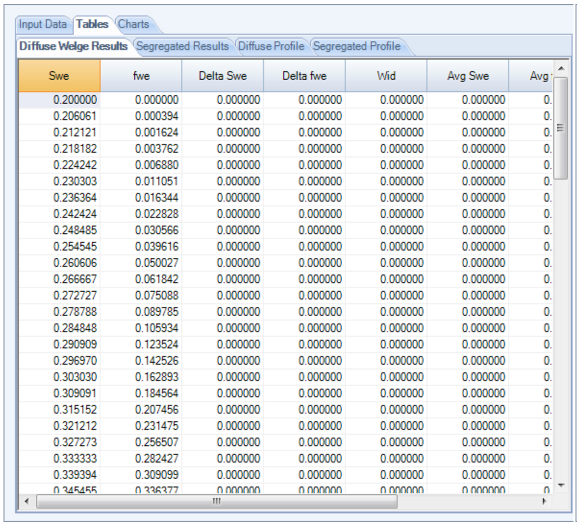
Once the user has successfully input all the required data, as shown in the following screen capture, they can press the ***calculate*** button to calculate all stages of the performance prediction.



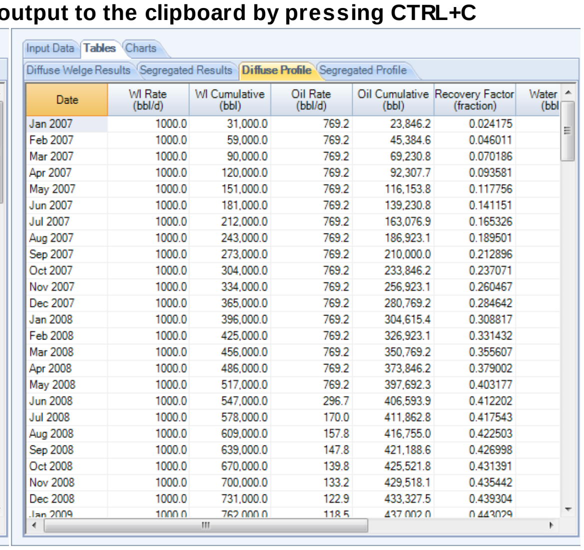
Diffuse Flow Results

The diffuse flow condition results are in the form of tables of Welge calculations and production profile, together with charts of Welge fractional flow and production profiles comparing both the diffuse and segregated flow conditions.

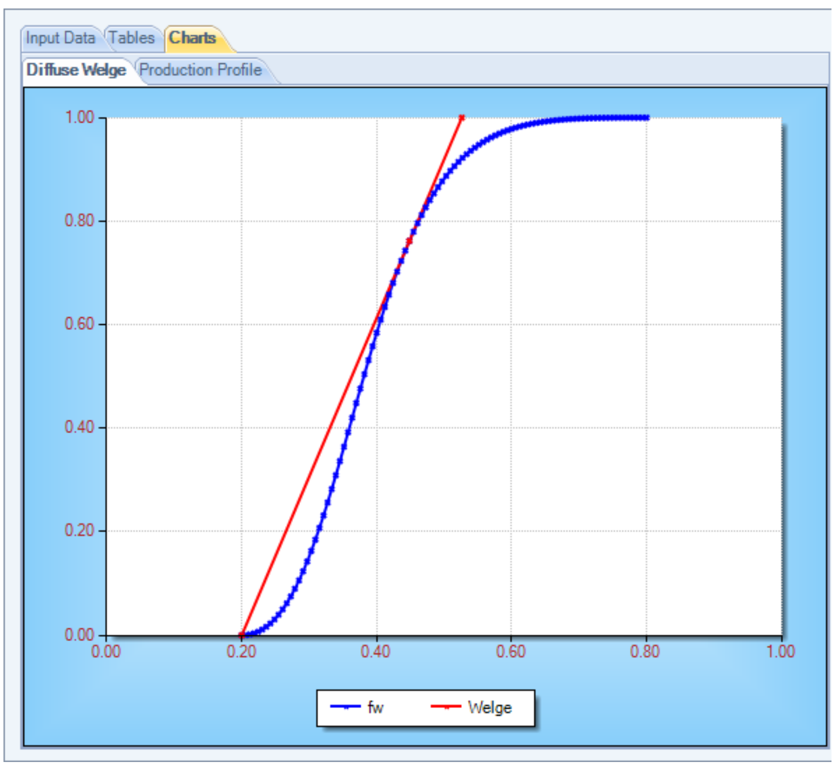
Note that all data within the tables can be output to the clipboard by pressing CTRL+C

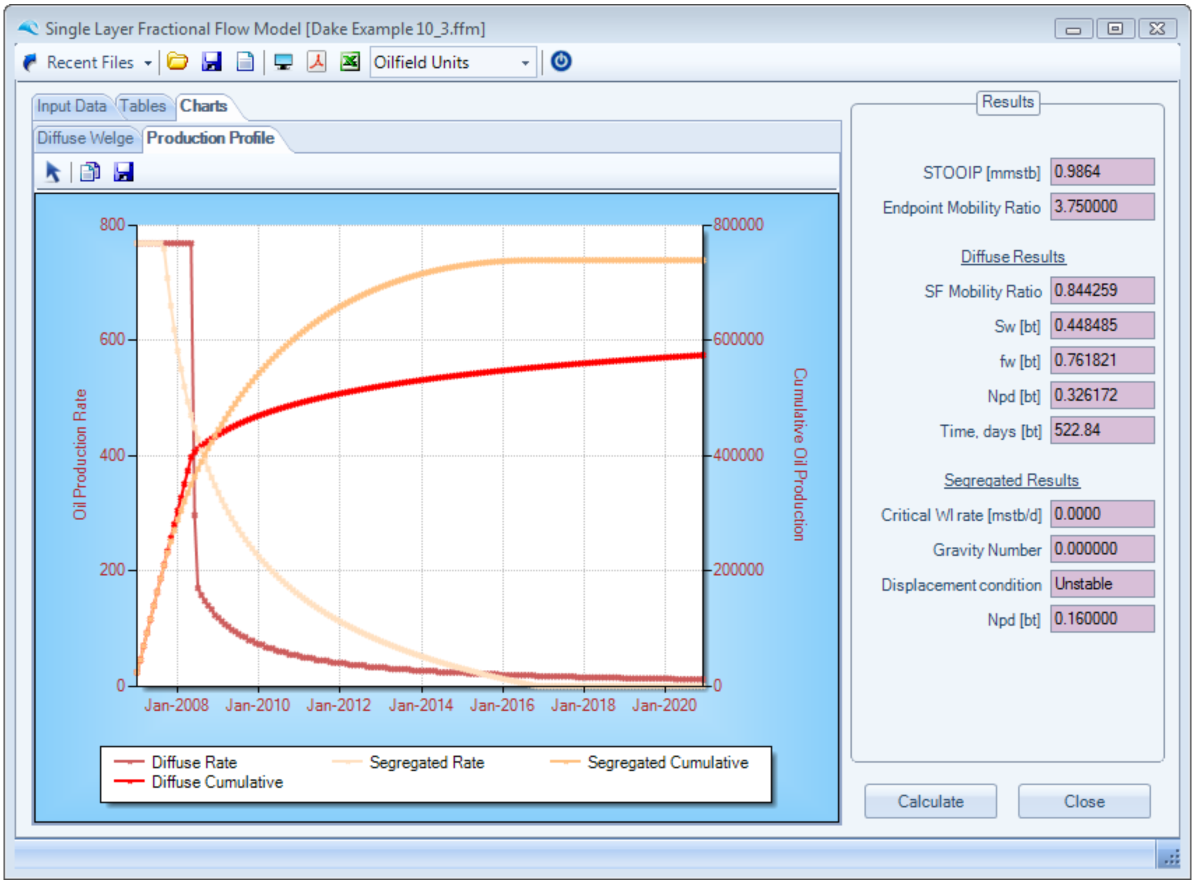


Swe	fwe	Delta Swe	Delta fwe	Wid	Avg Swe	Avg
0.200000	0.000000	0.000000	0.000000	0.000000	0.000000	0.
0.206061	0.000394	0.000000	0.000000	0.000000	0.000000	0.
0.212121	0.001624	0.000000	0.000000	0.000000	0.000000	0.
0.218182	0.003762	0.000000	0.000000	0.000000	0.000000	0.
0.224242	0.006880	0.000000	0.000000	0.000000	0.000000	0.
0.230303	0.011051	0.000000	0.000000	0.000000	0.000000	0.
0.236364	0.016344	0.000000	0.000000	0.000000	0.000000	0.
0.242424	0.022828	0.000000	0.000000	0.000000	0.000000	0.
0.248485	0.030566	0.000000	0.000000	0.000000	0.000000	0.
0.254545	0.039616	0.000000	0.000000	0.000000	0.000000	0.
0.260606	0.050027	0.000000	0.000000	0.000000	0.000000	0.
0.266667	0.061842	0.000000	0.000000	0.000000	0.000000	0.
0.272727	0.075088	0.000000	0.000000	0.000000	0.000000	0.
0.278788	0.089785	0.000000	0.000000	0.000000	0.000000	0.
0.284848	0.105934	0.000000	0.000000	0.000000	0.000000	0.
0.290909	0.123524	0.000000	0.000000	0.000000	0.000000	0.
0.296970	0.142526	0.000000	0.000000	0.000000	0.000000	0.
0.303030	0.162893	0.000000	0.000000	0.000000	0.000000	0.
0.309091	0.184564	0.000000	0.000000	0.000000	0.000000	0.
0.315152	0.207456	0.000000	0.000000	0.000000	0.000000	0.
0.321212	0.231475	0.000000	0.000000	0.000000	0.000000	0.
0.327273	0.256507	0.000000	0.000000	0.000000	0.000000	0.
0.333333	0.282427	0.000000	0.000000	0.000000	0.000000	0.
0.339394	0.309099	0.000000	0.000000	0.000000	0.000000	0.
0.345455	0.336377	0.000000	0.000000	0.000000	0.000000	0.



Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Recovery Factor (fraction)	Water (bbl
Jan 2007	1000.0	31,000.0	769.2	23,846.2	0.024175	
Feb 2007	1000.0	59,000.0	769.2	45,384.6	0.046011	
Mar 2007	1000.0	90,000.0	769.2	69,230.8	0.070186	
Apr 2007	1000.0	120,000.0	769.2	92,307.7	0.093581	
May 2007	1000.0	151,000.0	769.2	116,153.8	0.117756	
Jun 2007	1000.0	181,000.0	769.2	139,230.8	0.141151	
Jul 2007	1000.0	212,000.0	769.2	163,076.9	0.165326	
Aug 2007	1000.0	243,000.0	769.2	186,923.1	0.189501	
Sep 2007	1000.0	273,000.0	769.2	210,000.0	0.212896	
Oct 2007	1000.0	304,000.0	769.2	233,846.2	0.237071	
Nov 2007	1000.0	334,000.0	769.2	256,923.1	0.260467	
Dec 2007	1000.0	365,000.0	769.2	280,769.2	0.284642	
Jan 2008	1000.0	396,000.0	769.2	304,615.4	0.308817	
Feb 2008	1000.0	425,000.0	769.2	326,923.1	0.331432	
Mar 2008	1000.0	456,000.0	769.2	350,769.2	0.355607	
Apr 2008	1000.0	486,000.0	769.2	373,846.2	0.379002	
May 2008	1000.0	517,000.0	769.2	397,692.3	0.403177	
Jun 2008	1000.0	547,000.0	296.7	406,593.9	0.412202	
Jul 2008	1000.0	578,000.0	170.0	411,862.8	0.417543	
Aug 2008	1000.0	609,000.0	157.8	416,755.0	0.422503	
Sep 2008	1000.0	639,000.0	147.8	421,188.6	0.426998	
Oct 2008	1000.0	670,000.0	139.8	425,521.8	0.431391	
Nov 2008	1000.0	700,000.0	133.2	429,518.1	0.435442	
Dec 2008	1000.0	731,000.0	122.9	433,327.5	0.439304	
Jan 2009	1000.0	762,000.0	118.5	437,002.0	0.443029	

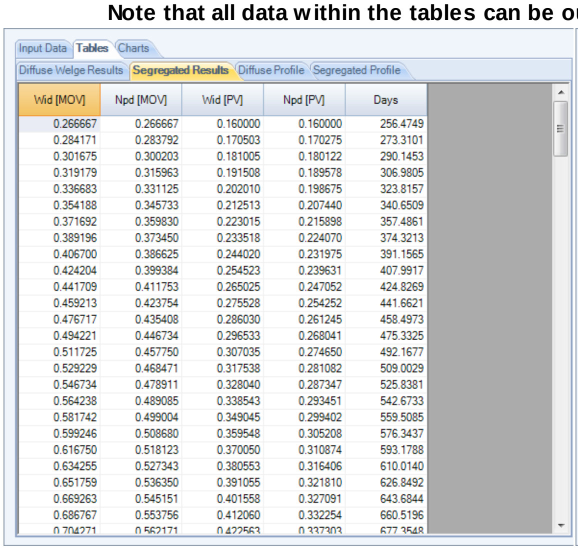




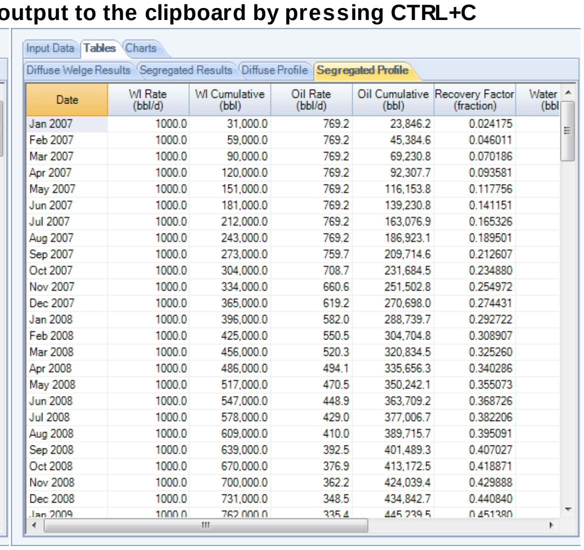
Segregated Flow Results

The segregated flow condition results are in the form of tables of Dake calculations and production profile, together with a production profile chart comparing both the diffuse and segregated flow conditions.

Note that all data within the tables can be output to the clipboard by pressing CTRL+C



Wid [MOV]	Npd [MOV]	Wid [PV]	Npd [PV]	Days
0.266667	0.266667	0.160000	0.160000	256.4749
0.284171	0.283792	0.170503	0.170275	273.3101
0.301675	0.300203	0.181005	0.180122	290.1453
0.319179	0.315963	0.191508	0.189578	306.9805
0.336683	0.331125	0.202010	0.198675	323.8157
0.354188	0.345733	0.212513	0.207440	340.6509
0.371692	0.359830	0.223015	0.215898	357.4861
0.389196	0.373450	0.233518	0.224070	374.3213
0.406700	0.386625	0.244020	0.231975	391.1565
0.424204	0.399384	0.254523	0.239631	407.9917
0.441709	0.411753	0.265025	0.247052	424.8269
0.459213	0.423754	0.275528	0.254252	441.6621
0.476717	0.435408	0.286030	0.261245	458.4973
0.494221	0.446734	0.296533	0.268041	475.3325
0.511725	0.457750	0.307035	0.274650	492.1677
0.529229	0.468471	0.317538	0.281082	509.0029
0.546734	0.478911	0.328040	0.287347	525.8381
0.564238	0.489085	0.338543	0.293451	542.6733
0.581742	0.499004	0.349045	0.299402	559.5085
0.599246	0.508680	0.359548	0.305208	576.3437
0.616750	0.518123	0.370050	0.310874	593.1788
0.634255	0.527343	0.380553	0.316406	610.0140
0.651759	0.536350	0.391055	0.321810	626.8492
0.669263	0.545151	0.401558	0.327091	643.6844
0.686767	0.553756	0.412060	0.332254	660.5196
0.704271	0.562171	0.422563	0.337303	677.3548



Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Recovery Factor (fraction)	Water (bbl
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Jun 2007	1000.0	181,000.0	769.2	139,230.8	0.141151	
Jul 2007	1000.0	212,000.0	769.2	163,076.9	0.165326	
Aug 2007	1000.0	243,000.0	769.2	186,923.1	0.189501	
Sep 2007	1000.0	273,000.0	759.7	209,714.6	0.212607	
Oct 2007	1000.0	304,000.0	708.7	231,684.5	0.234880	
Nov 2007	1000.0	334,000.0	660.6	251,502.8	0.254972	
Dec 2007	1000.0	365,000.0	619.2	270,698.0	0.274431	
Jan 2008	1000.0	396,000.0	582.0	288,739.7	0.292722	
Feb 2008	1000.0	425,000.0	550.5	304,704.8	0.308907	
Mar 2008	1000.0	456,000.0	520.3	320,834.5	0.325260	
Apr 2008	1000.0	486,000.0	494.1	335,656.3	0.340286	
May 2008	1000.0	517,000.0	470.5	350,242.1	0.355073	
Jun 2008	1000.0	547,000.0	448.9	363,709.2	0.368726	
Jul 2008	1000.0	578,000.0	429.0	377,006.7	0.382206	
Aug 2008	1000.0	609,000.0	410.0	389,715.7	0.395091	
Sep 2008	1000.0	639,000.0	392.5	401,489.3	0.407027	
Oct 2008	1000.0	670,000.0	376.9	413,172.5	0.418871	
Nov 2008	1000.0	700,000.0	362.2	424,039.4	0.429888	
Dec 2008	1000.0	731,000.0	348.5	434,842.7	0.440840	
Jan 2009	1000.0	762,000.0	335.4	445,239.5	0.451380	

2.2 Multi Layer Fractional Flow Model

The following text is taken directly from the Waterdrive chapter of Dake's "The Practice of Reservoir Engineering", and very appropriately describes the purpose of this section.

"The previous section described the basic theory of waterdrive on the scale of a one-dimensional core flooding experiment. The same theory of Buckley-Leverett and the practical application technique of Welge will now be extended to the description of waterflooding in macroscopic, heterogeneous reservoir sections, which is a two-dimensional problem. In this respect, the engineer must be aware that in practice, waterflooding is conducted in "hillsides", not core plugs and the efficiency of the process is governed by three physical factors, namely:

- *mobility ratio (M)*
- *heterogeneity*
- *gravity"*

Dake goes on to present a *recipe* for evaluating vertical sweep efficiency in heterogeneous reservoirs, which is listed below, and forms the basis for how the routines contained within this sections are structured.

"No matter what the nature of the vertical heterogeneity, the following recipe is applied to assess the sweep efficiency in edge waterdrive reservoirs.

- *Divide the section in to N layers, each characterised by the following parameters: thickness, permeability, porosity, Swc, Sor, krw', kro'.*
- *Decide whether there is vertical pressure communication between the layers or not.*
- *Decide upon the flooding order of the N layers and generate pseudo-relative permeabilities to reduce the description of the macroscopic displacement to one dimension.*
- *Use the pseudos to generate a fractional flow relationship which is used in the Welge equation to calculate the oil recovery, Npd as a function of cumulative water influx, Wid.*
- *Convert the oil volume to a fractional oil recovery, Np/N, and relate this to the surface watercut, fws."*

References:

Dake, L., *"The Practice of Reservoir Engineering",* Elsevier Scientific Publishing Company, 1994.

2.2.1 Introduction

Dake's recipe for evaluating vertical sweep efficiency in heterogeneous reservoirs is listed below.

"No matter what the nature of the vertical heterogeneity, the following recipe is applied to assess the sweep efficiency in edge waterdrive reservoirs.

- Divide the section in to N layers, each characterised by the following parameters: thickness, permeability, porosity, Swc, Sor, krw', kro'.
- Decide whether there is vertical pressure communication (Vertical Equilibrium or VE) between the layers or not.
- Decide upon the flooding order of the N layers and generate pseudo-relative permeabilities to reduce the description of the macroscopic displacement to one dimension.
- Use the pseudos to generate a fractional flow relationship which is used in the Welge equation to calculate the oil recovery, Npd as a function of cumulative water influx, Wid.
- Convert the oil volume to a fractional oil recovery, Np/N, and relate this to the surface watercut, fws."

The Vertical Equilibrium (VE) condition means that the order in which the N selected layers flood is from the base layer to the top layer of the reservoir system. VE implies the dominance of gravity, however at no stage does a vertical gravity term appear in any of the displacement equations. Instead, all that is necessary is recognition of the fact that the water density is greater than the oil density, therefore water will naturally slump to the base of the reservoir and this dictates the flooding order of the selected layers.

If the selected layers are vertically isolated from one another, so that there is a total lack of cross-flow, then the order in which the layers flood out is determined by the actual velocity of the frontal advance of water in each layer. See equation below.

$$v_i = \frac{k_i k'_{rw_i}}{\phi_i \left(1 - S_{or_i} - S_{wc_i}\right)}$$

The dependence on permeability in the above equation is obvious. However concerning the terms in the denominator, low porosity rock, having a smaller capacity, will flood faster than high capacity, and similarly the smaller the movable saturation the more rapid the advance of water. The layers will therefore flood in decreasing sequence of their calculated values of velocity.

Having determined the flooding order of the layers the next step is to generate thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive.

Four methods are provided to generate a fractional flow relationship, namely Heterogeneous and Homogeneous methods where there is vertical pressure communication between layers (Vertical Equilibrium or VE), and Stiles and Dykstra-Parsons methods where there is a complete lack of pressure communication between layers.

Once the fractional flow and Welge calculations have been performed, then the user can history match the field STOOIP value from a knowledge of the fields production and injection history, and finally can predict the future performance of the field via a knowledge of the production and injection constraints. This history matching and prediction performance is highlighted in more detail in the worked example.

2.2.2 Heterogeneous with Vertical Equilibrium

The equations to calculate the thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive, where the nth layer out of a total of N has flooded with water are given below :

$$\bar{S}_{w_n} = \frac{\sum_{i=1}^{n} h_i \phi_i \left(1 - S_{or_i}\right) + \sum_{i=n+1}^{N} h_i \phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i \phi_i}$$

$$\bar{k}_{rw_n} = \frac{\sum_{i=1}^{n} h_i k_i k'_{rw_i}}{\sum_{i=1}^{N} h_i k_i} \qquad \bar{k}_{ro_n} = \frac{\sum_{i=n+1}^{N} h_i k_i k'_{ro_i}}{\sum_{i=1}^{N} h_i k_i}$$

Where for waterdrive in an inclined reservoir, if the displacement is in the more gravity stable updip direction, then the equation for the fractional flow of water is as follows :

$$f_{we_n} = \frac{1 - \dfrac{\bar{k}.\bar{k}_{ro}.A}{q_t.\mu_o} \cdot \dfrac{\Delta\rho.g.\sin\theta}{1.0133\times10^6}}{1 + \dfrac{\mu_o}{\bar{k}_{rw_n}} \cdot \dfrac{\bar{k}_{ro_n}}{\mu_w}}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\bar{S}_{we} - \bar{S}_{wc}\right) + \left(1 - \bar{f}_{we}\right)W_{id}}{\left(1 - \bar{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\Delta\bar{f}_{we} \big/ \Delta\bar{S}_{we}\right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \dfrac{B_w}{B_o}\left(\dfrac{1}{\bar{f}_{we}} - 1\right)}$$

Catering for the Presence of Edge Water in VE Waterdrive

Dake proposed the following modification of the standard Welge equation to account for edge water in a dipping reservoir undergoing vertical equilibrium displacement.

$$N'_{pd} = N_{pd}\left(1 - \frac{h}{2.L.\tan\theta}\right)$$

$$W'_{id} = W_{id} - \frac{h}{2.L.\tan\theta}\left(1 - S_{or} - S_{wc}\right)$$

2.2.3 Homogeneous with Vertical Equilibrium

The equations to calculate the thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive, where the nth layer out of a total of N has flooded with water are given below :

$$\bar{S}_{w_n} = \frac{\sum_{i=1}^{n} h_i \phi_i \left(1 - S_{or_i}\right) + \sum_{i=n+1}^{N} h_i \phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i \phi_i}$$

$$\bar{k}_{rw_n} = \left(\frac{\bar{S}_{w_n} - S_{wc}}{1 - S_{or} - S_{wc}}\right).k'_{rw} \quad \bar{k}_{ro_n} = \left(\frac{1 - S_{or} - \bar{S}_{w_n}}{1 - S_{or} - S_{wc}}\right).k'_{ro}$$

Where for waterdrive in an inclined reservoir, if the displacement is in the more gravity stable updip direction, then the equation for the fractional flow of water is as follows :

$$f_{we_n} = \frac{1 - \dfrac{\bar{k}.\bar{k}_{ro}.A}{q_t.\mu_o}.\dfrac{\Delta\rho.g.\sin\theta}{1.0133\times 10^6}}{1 + \dfrac{\mu_o}{\bar{k}_{rw_n}}.\dfrac{\bar{k}_{ro_n}}{\mu_w}}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\bar{S}_{we} - \bar{S}_{wc}\right) + \left(1 - \bar{f}_{we}\right)W_{id}}{\left(1 - \bar{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\Delta\bar{f}_{we} / \Delta\bar{S}_{we}\right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \dfrac{B_w}{B_o}\left(\dfrac{1}{\bar{f}_{we}} - 1\right)}$$

Catering for the Presence of Edge Water in VE Waterdrive

Dake proposed the following modification of the standard Welge equation to account for edge water in a dipping reservoir undergoing vertical equilibrium displacement.

$$N'_{pd} = N_{pd}\left(1 - \frac{h}{2.L.\tan\theta}\right)$$

$$W'_{id} = W_{id} - \frac{h}{2.L.\tan\theta}\left(1 - S_{or} - S_{wc}\right)$$

2.2.4 Stiles Method

The Stiles method is restricted to reservoirs with no vertical pressure communication between layers and where the mobility ratio is close to a value of one. The mobility ratio assumption ensures that the velocity of frontal advance of water in each layer remains constant during the flood. That is, the velocities will be different in each layer, as dictated by the following equation, but as the flood progresses the differences between layers will remain constant: ie., there is no velocity dispersion.

$$v_i = \frac{k_i k'_{rw_i}}{\phi_i\left(1 - S_{or_i} - S_{wc_i}\right)}$$

The Stiles procedure is as follows :

1. Inspect the core and log data and divide the section into a total of N separate layers
2. Order the N layers in the sequence in which they will successively flood-out with water, by applying the above velocity equation.
3. Generate pseudo-relative permeabilities by applying the following equations.

$$\bar{S}_{w_n} = \frac{\sum_{i=1}^{n} h_i\phi_i\left(1 - S_{or_i}\right) + \sum_{i=n+1}^{N} h_i\phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i\phi_i}$$

$$\bar{k}_{rw_n} = \frac{\sum_{i=1}^{n} h_i k_i k'_{rw_i}}{\sum_{i=1}^{N} h_i k_i} \qquad \bar{k}_{ro_n} = \frac{\sum_{i=n+1}^{N} h_i k_i k'_{ro_i}}{\sum_{i=1}^{N} h_i k_i}$$

The only difference between Stiles and Heterogeneous VE pseudo-generation is in the flooding order in which the procedures are evaluated.

It is also apparent that, with the exception of gravity within each sand layer, gravity plays no part in the Stiles type displacement on account of the vertical separation of the layers. This results in the displacement efficiency being entirely dictated by the mobility ratio and heterogeneity. Therefore the equation for the fractional flow of water is simplified as follows :

$$f_{we_n} = \frac{1}{1 + \frac{\mu_o}{\bar{k}_{rw_n}} \cdot \frac{\bar{k}_{ro_n}}{\mu_w}}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{(\bar{S}_{we} - \bar{S}_{wc}) + (1 - \bar{f}_{we}).W_{id}}{(1 - \bar{S}_{wc})}$$

where.

$$Wid = \frac{1}{\left(\Delta\bar{f}_{we} \middle/ \Delta\bar{S}_{we} \right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o}\left(\frac{1}{\bar{f}_{we}} - 1 \right)}$$

2.2.5 Dykstra-Parsons Method

The Dykstra-Parsons method is the general approach to calculating vertical sweep efficiency in reservoirs with no vertical pressure communication between layers, since it is appropriate for all values of the mobility ratio. It therefore caters for velocity dispersion of the flood front between the individual layers.

The Dykstra-Parsons procedure is as follows :

1. Inspect the core and log data and divide the section into a total of N separate layers
2. Order the N layers in the sequence in which they will successively flood-out with water, by applying the following velocity equation.

$$\lambda = \frac{k.k'_{rw}}{\phi.\Delta S_w}$$

3. As each layer floods, calculate the frontal positions in all the remaining unflooded layers by solution of the following quadratic equation :

$$\frac{1}{2}Ax_j^{\,2} + x_j = \frac{\lambda_j}{\lambda_i}\left(\frac{1}{2}A + 1 \right)$$

where A is defined as :

$$A = \frac{1}{M} - 1$$

4. Calculate the fractional flow, which for a section of fixed width and individual layer thickness, h_i, may be evaluated using the following equation :

$$f_{we_n} = \frac{\sum_{i=1}^{n} \frac{\lambda_i h_i}{A+1}}{\sum_{i=1}^{N} \frac{\lambda_i h_i}{Ax_i + 1}} \approx \frac{\sum_{i=1}^{n} \frac{k_i h_i}{A+1}}{\sum_{i=1}^{N} \frac{k_i h_i}{Ax_i + 1}}$$

which is the condition pertaining after the n^{th} layer out of a total of N has flooded. According to Dake, since the kh-product is predominant over the other parameters, the second expression is usually a perfectly acceptable approximation.

5. The corresponding thickness averaged water saturation can be calculated using the following equation :

$$\bar{S}_{w_n} = \frac{\sum_{i=1}^{n} h_i \phi_i \left(1 - S_{or_i}\right) + \sum_{i=n+1}^{N} h_i \phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i \phi_i}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\bar{S}_{we} - \bar{S}_{wc}\right) + \left(1 - \bar{f}_{we}\right) W_{id}}{\left(1 - \bar{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\Delta \bar{f}_{we} / \Delta \bar{S}_{we} \right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o}\left(\frac{1}{\bar{f}_{we}} - 1\right)}$$

2.2.6 Example

In Chapter 5 Waterdrive of Dake's *"The Practice of Reservoir Engineering"*, he provides the following example.

General Input Data

Oil Density, gm/cc	0.7
Water Density, gm/cc	1.02
Oil Viscosity [cP]	1.24
Water Viscosity [cP]	0.41
Oil FVF, Bo rb/stb	1.475
Water FVF, Bw rb/stb	1.03
Water FVF, Bw rb/stb	1.03
Reservoir Length [ft]	4000
Reservoir Width [ft]	1000
Reservoir Dip, degrees	10
Injection Rate [stb/d]	6000
Selected Method	Stiles
STOOIP [mmstb]	176
Use Areal Sweep Correlation ?	True
Select Pattern Method	Direct Line Drive

Layer Input Data

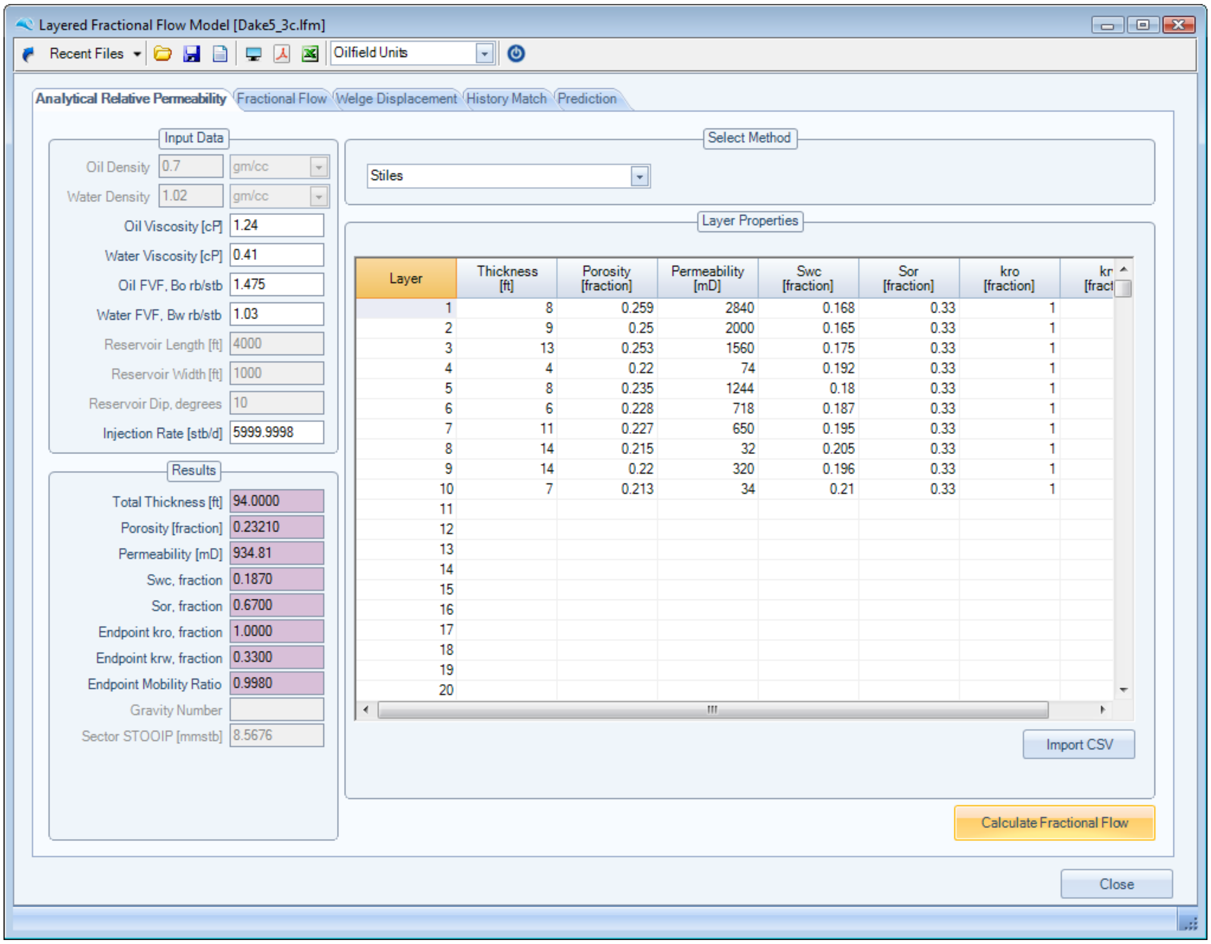
Layer	Thickness [ft]	Porosity [fraction]	Permeability [mD]	Swc [fraction]	Sor [fraction]	kro [fraction]	krw [fraction]
1	8	0.259	2840	0.168	0.33	1	0.33
2	9	0.25	2000	0.165	0.33	1	0.33
3	13	0.253	1560	0.175	0.33	1	0.33
4	4	0.22	74	0.192	0.33	1	0.33
5	8	0.235	1244	0.18	0.33	1	0.33
6	6	0.228	718	0.187	0.33	1	0.33
7	11	0.227	650	0.195	0.33	1	0.33
8	14	0.215	32	0.205	0.33	1	0.33
9	14	0.22	320	0.196	0.33	1	0.33
10	7	0.213	34	0.21	0.33	1	0.33

Problem Statement

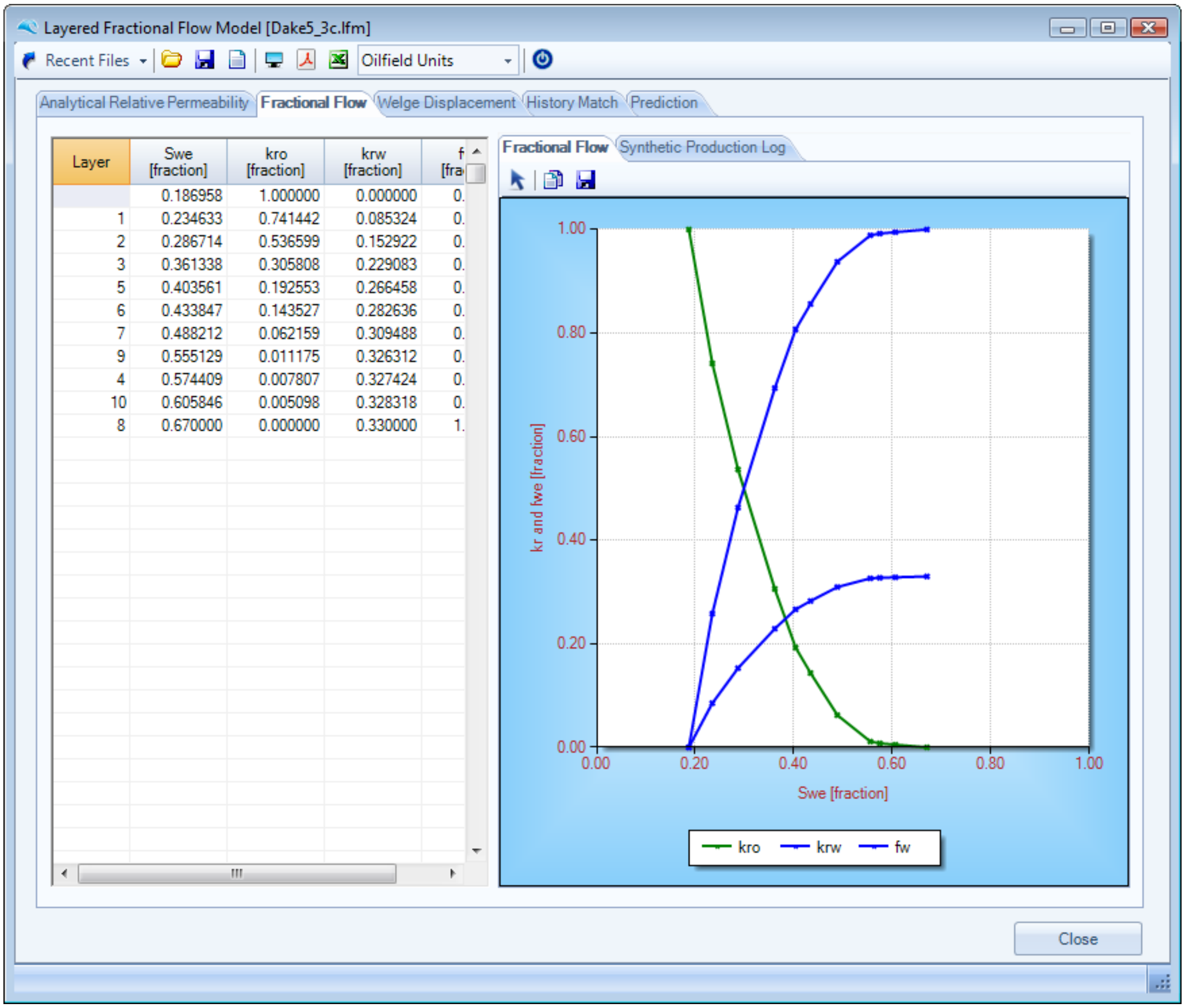
For the above data, calculate :

1. the reservoir fractional flow and resultant oil recovery versus watercut relationships assuming a Stiles, no vertical pressure communication between layers, method,
2. the likely field STOOIP value, given a knowledge of the production history.
3. the future oil, water, liquid production and water injection profiles assuming the following facilities constraints; 60mbbl/d oil, 60mbbl/d water and 65mbbl/d liquid production and 65mbbl/d water injection.

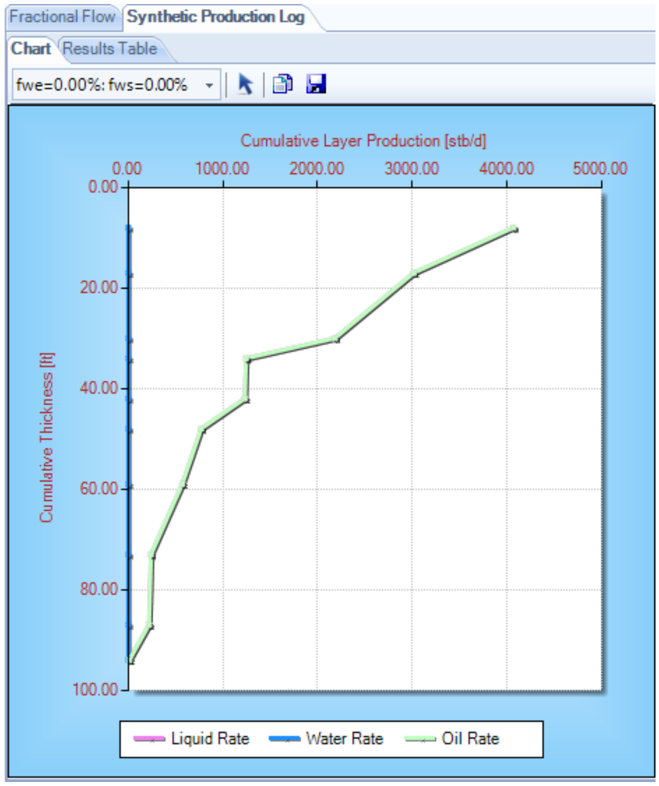
Once the user has input all the necessary input data, they should press the Calculate button, as shown below. Note that the layer data can be copied and pasted into the input table by pressing the windows standard shortcut keys [CTRL+C] then [CTRL+V].



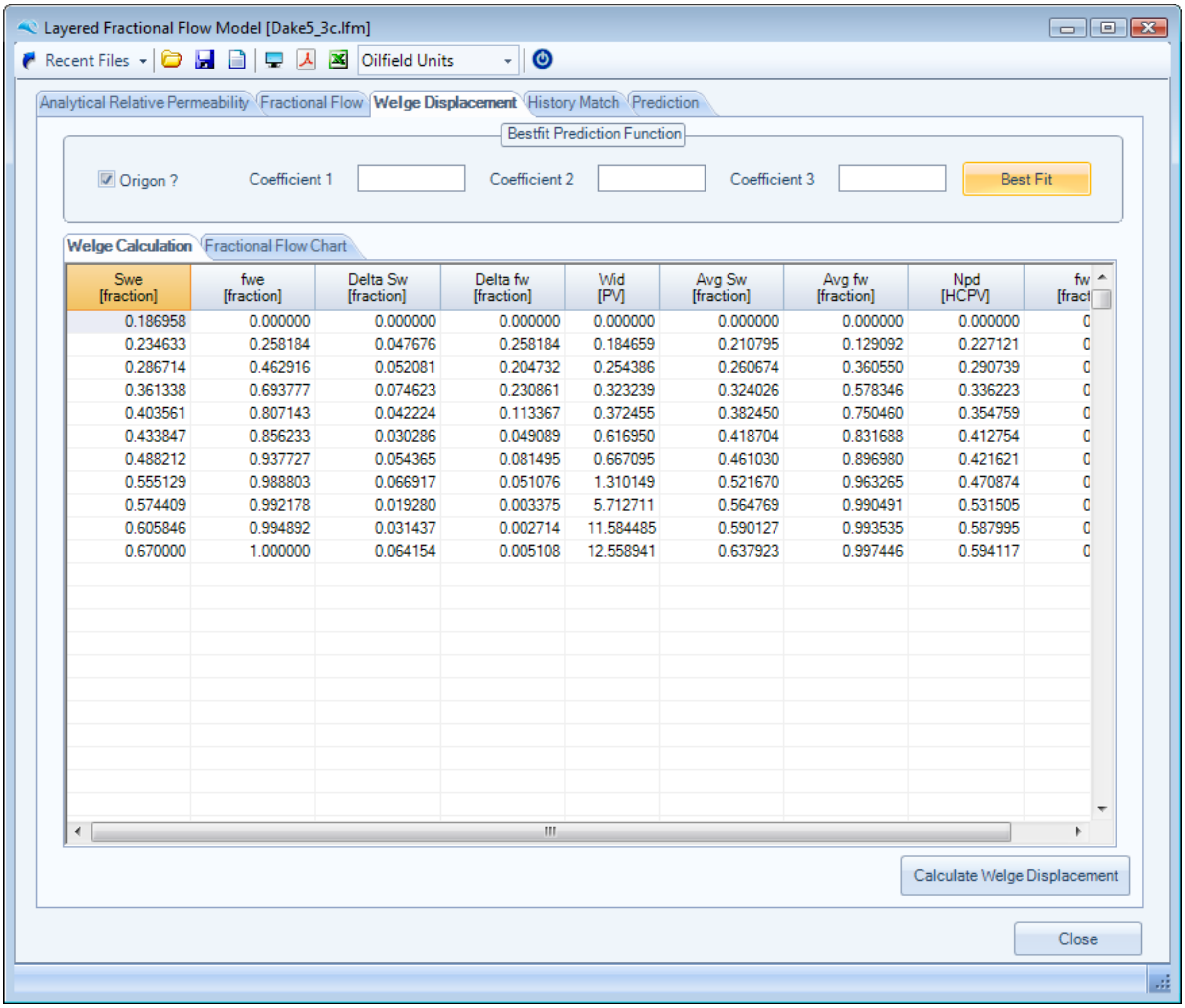
The fractional flow data will be calculated and displayed in the following TAB, as shown below.



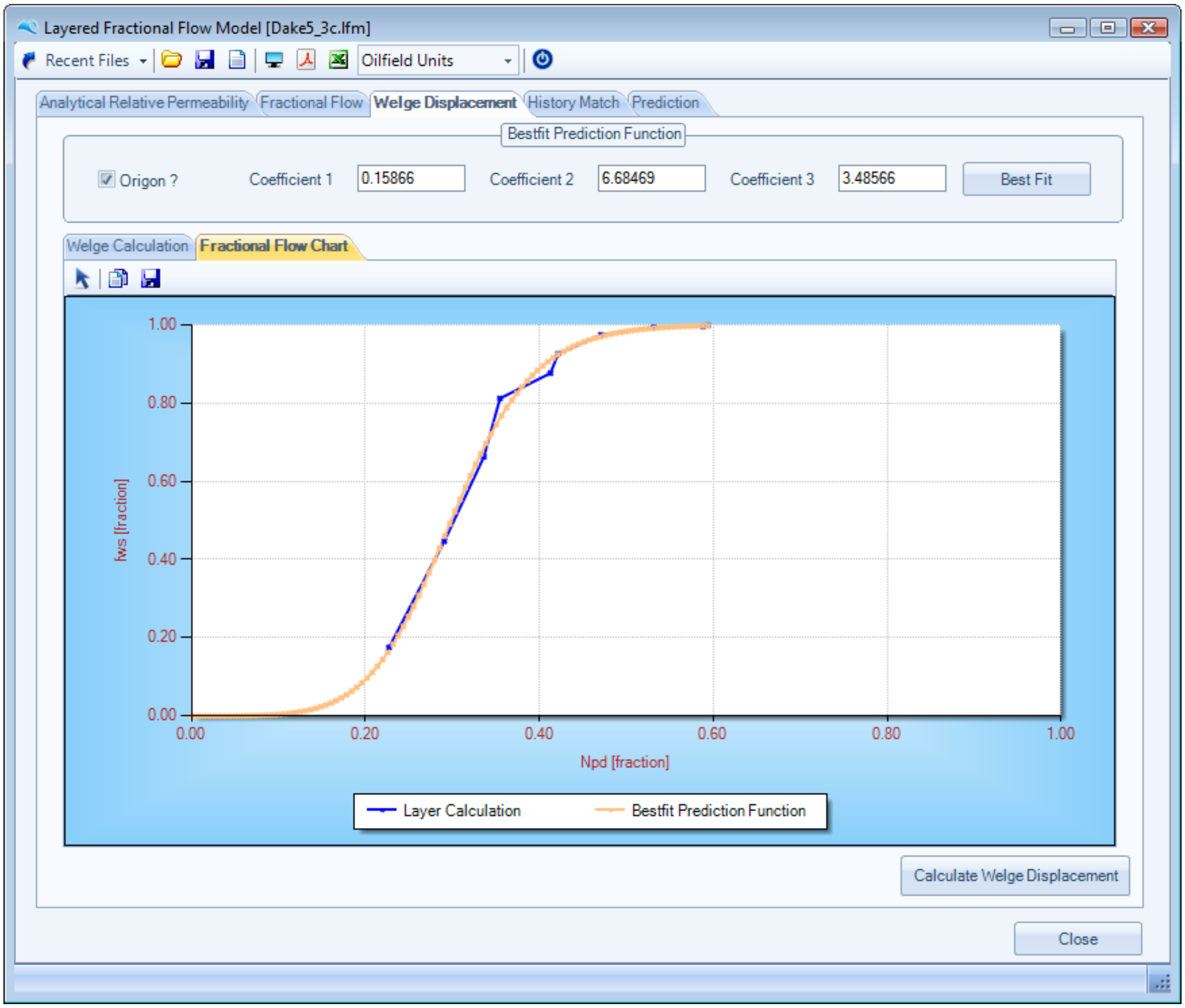
Since all the required data has been input to calculate synthetic production log versus various watercut values based on each layer's water breakthrough, we have provided the display and layer calculations for these synthetic production logs. See example provided below.



Once the fractional flow data has been successfully calculated, proceed to the next TAB, Welge Displacement, as shown below, and press the *Calculate Welge Displacement* button.



The user can choose to bestfit a regression equation to better describe the Npd Vs fws relationship, for later use in the prediction calculations, see following screen capture.

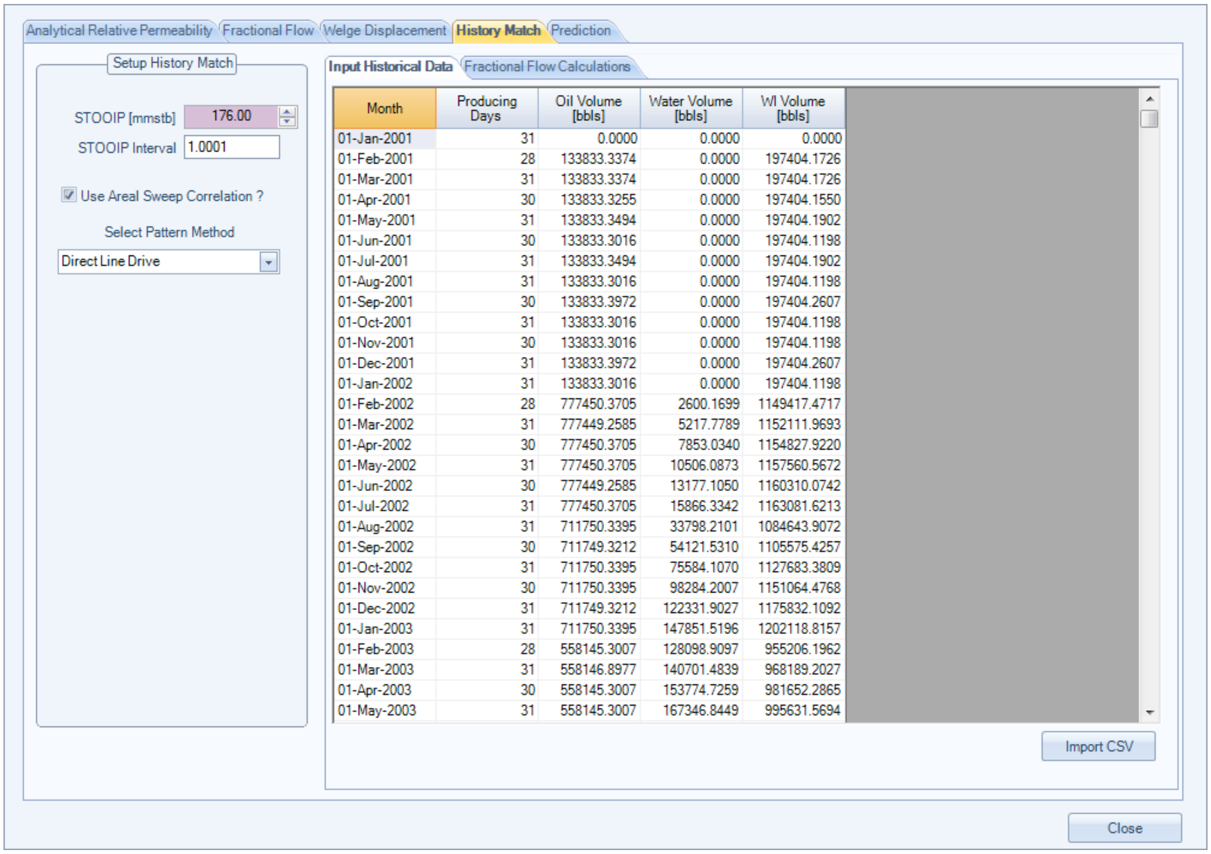


The ***Bestfit*** button returns the coefficients (C1, C2 and C3) of the following equation :

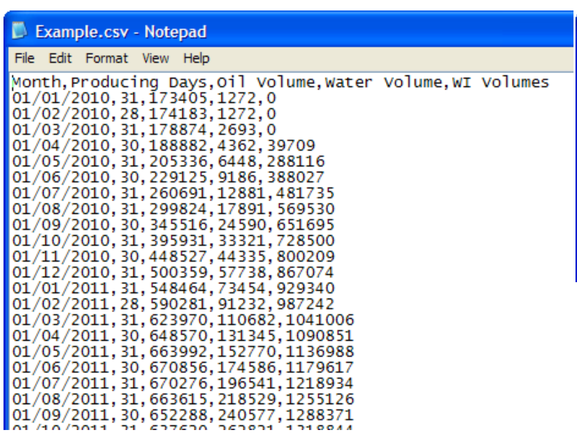
$$f_{ws} = \left(1 + C_1.\left[\frac{(1 - N_{pd})^{C_2}}{N_{pd}{}^{C_3}}\right]\right)^{-1}$$

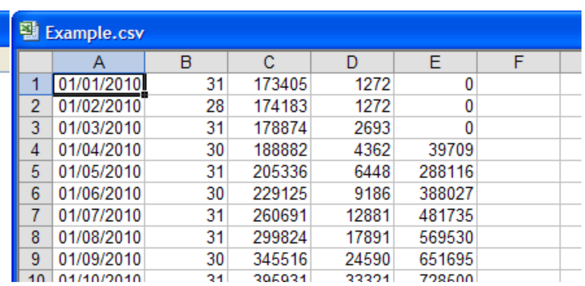
History Matching

If the oilfield under study is a producing field and the monthly values of production and injection history are known, then the User can choose to history match the total field oil originally in place, STOOIP. This is illustrated in the following screen captures. Firstly enter the monthly production and injection history, as per the format shown below, either by importing via a comma delimited ASCII file and by pressing the Import CSV button, or via copy [CTRL+C] and paste [CTRL+V] from an external application such as Microsoft Excel into the data input table below.

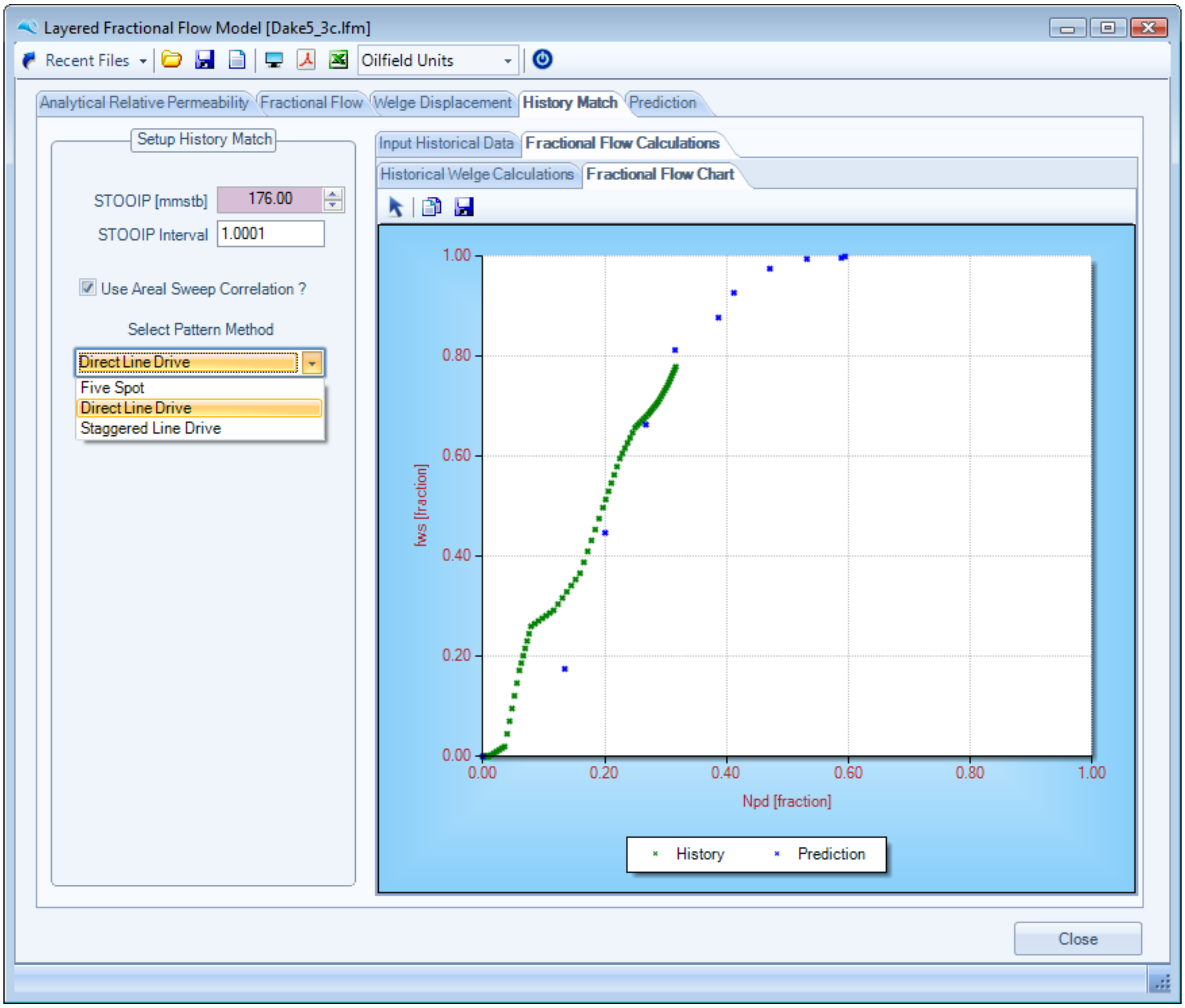


Example formats of comma delimited ASCII file (CSV) file are shown below.



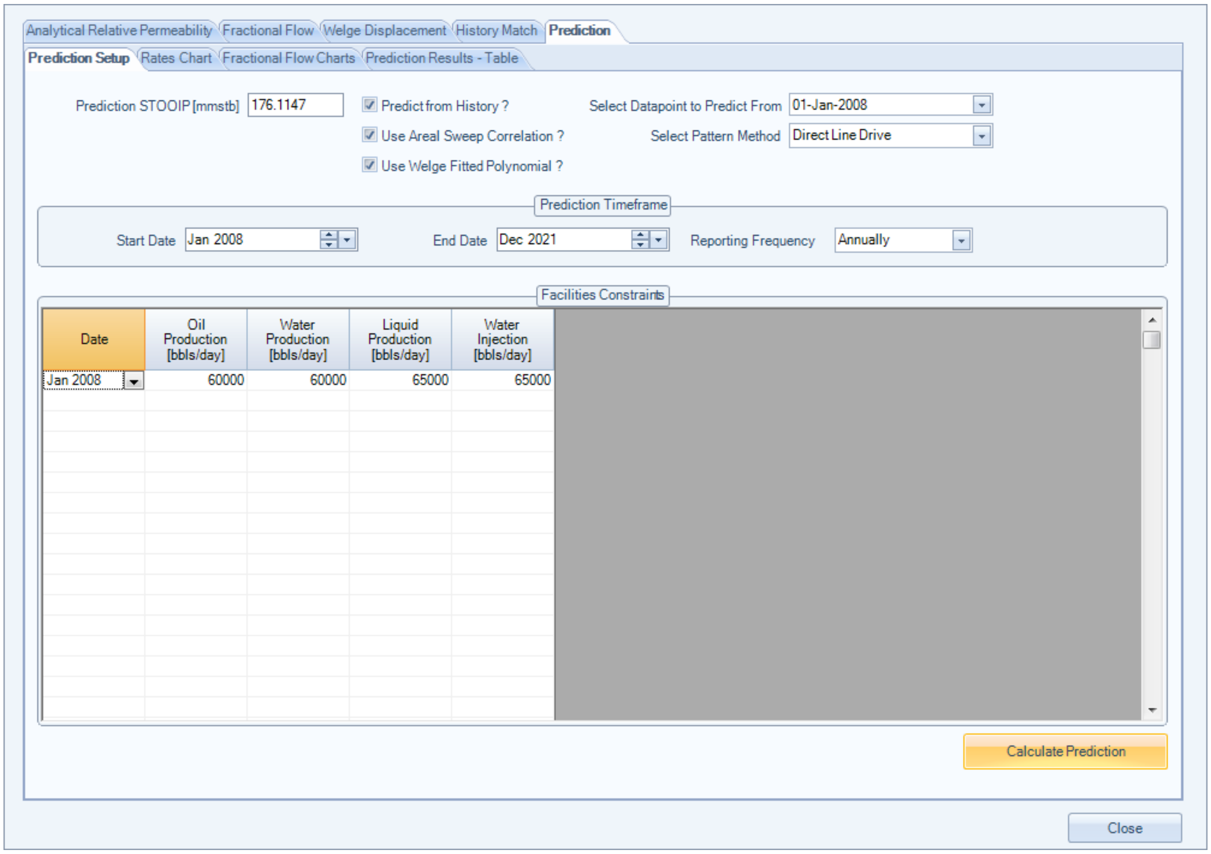


The user can then iterate the STOOIP value by selecting the up and down buttons adjacent to the STOOIP value, as shown below, to iterate the fractional flow history match. The user can also choose to modify the vertical layer predicted values of fws Vs NpD by applying an areal sweep correlation. To enable this option simply select the Use Areal Sweep Correlation check box and then select the waterdrive pattern; namely 5 spot, direct line drive or staggered line drive.

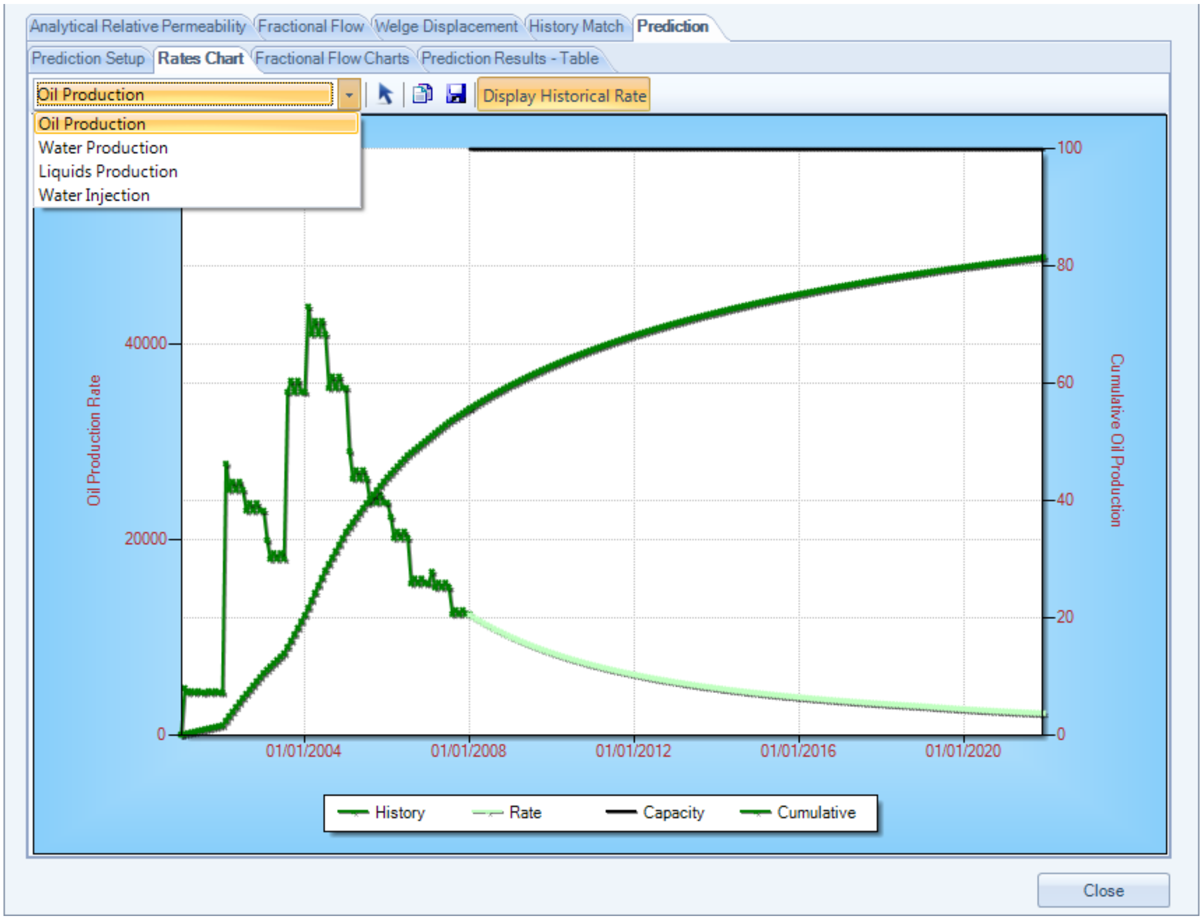


Prediction Performance

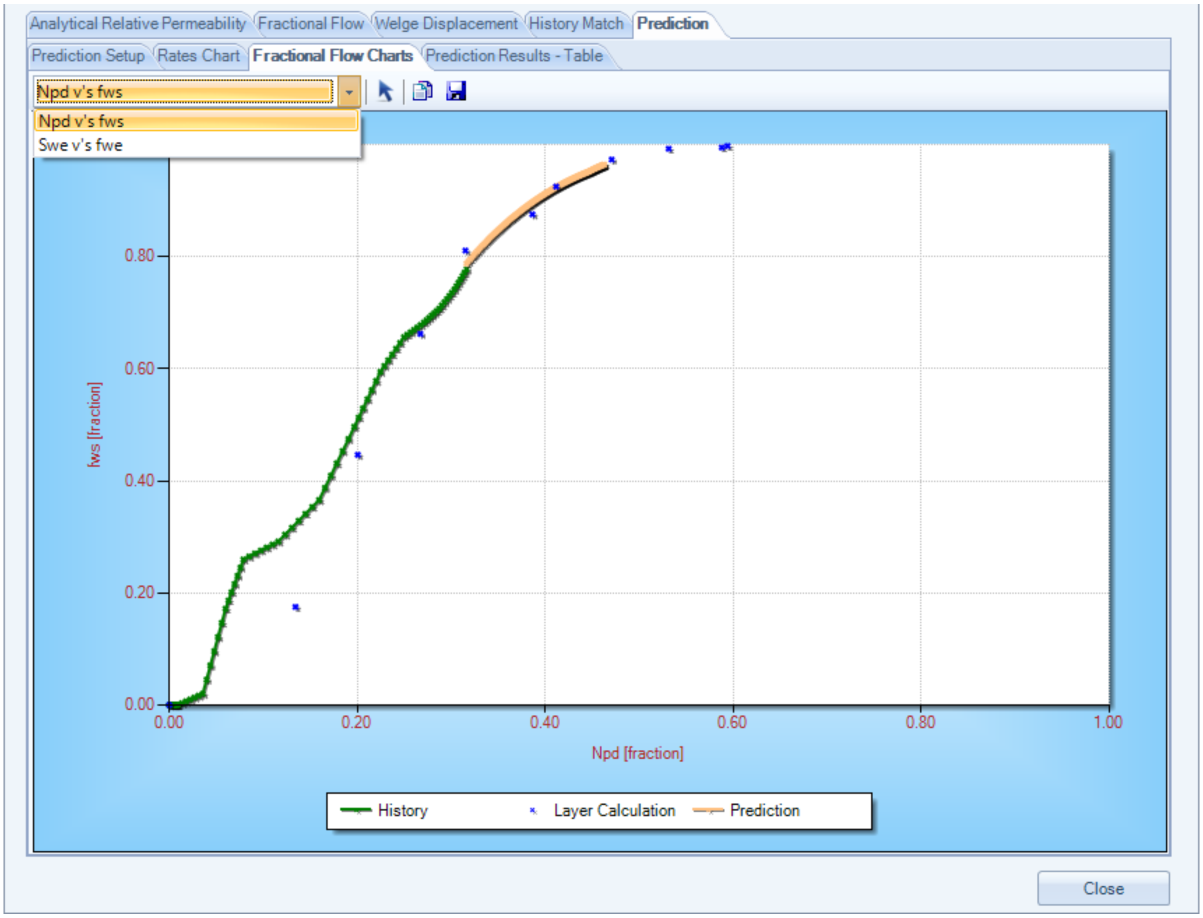
To calculate the prediction performance, select the Prediction tab. Enter appropriate values for STOOIP, check whether to predict values from History, whether to use an areal sweep correlation in the prediction calculations, and whether to use the best fit Welge polynomial calculated in the Welge Displacement tab. Once the prediction timeframe has been entered together with the facilities constraints, the user can press the Calculate Prediction button, as shown below.

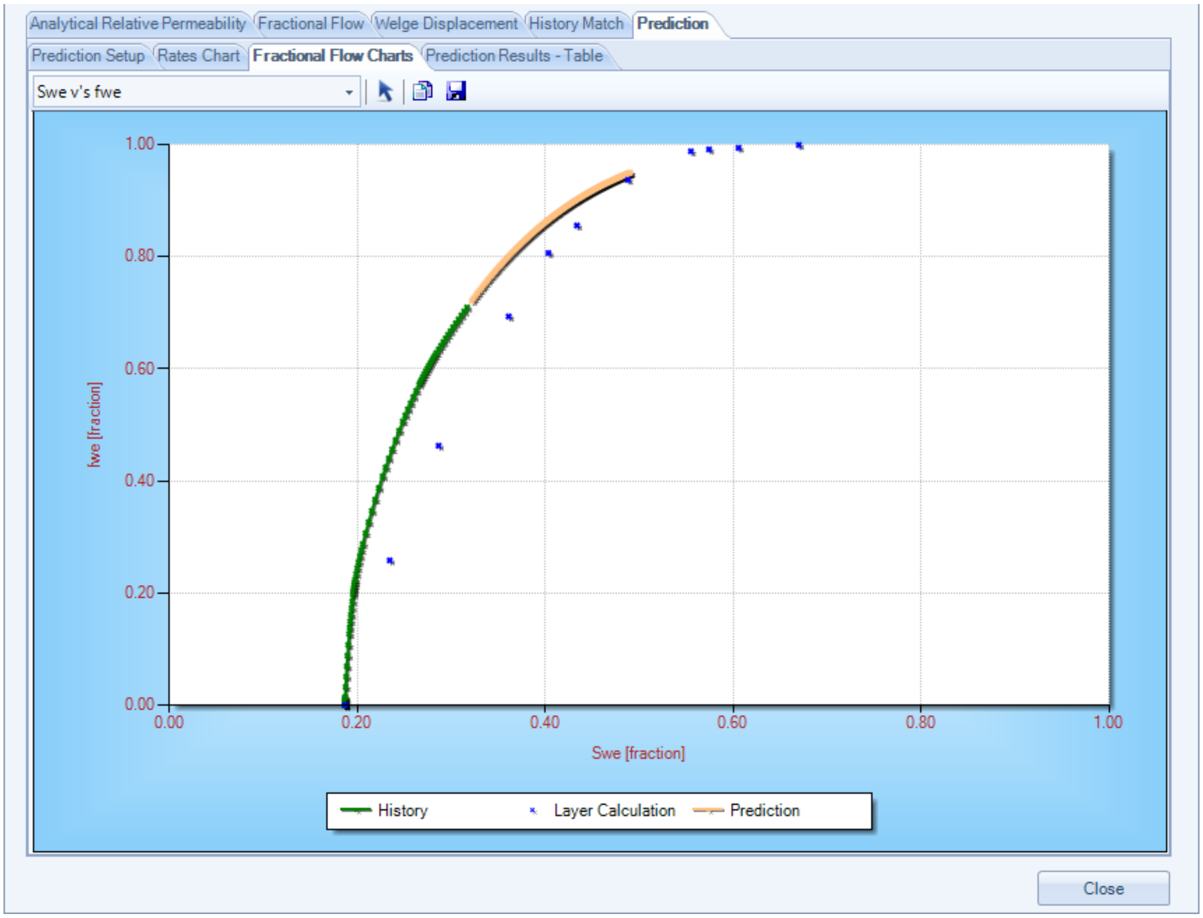


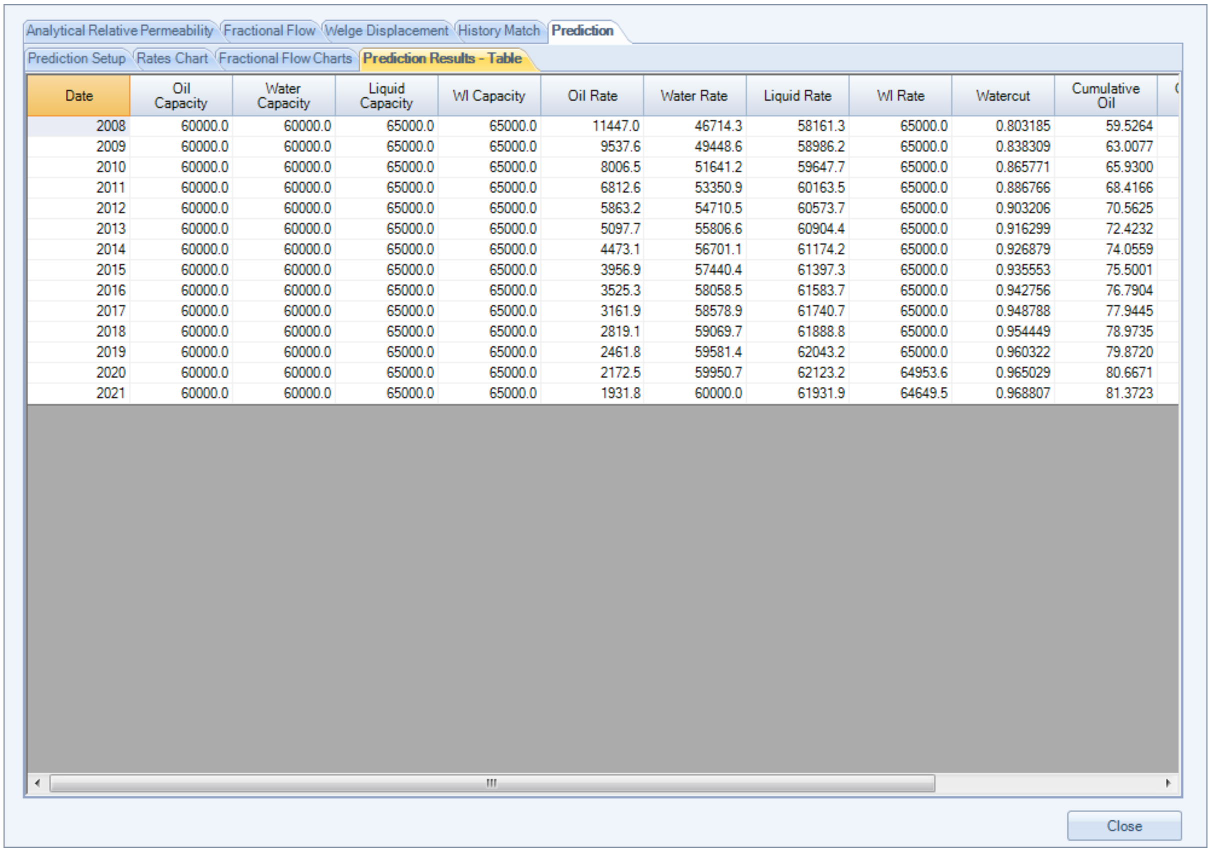
Various charts and tables of prediction output are shown as examples below.


Analytical Relative Permeability
Fractional Flow
Welge Displacement
History Match
Prediction
Prediction Setup
Rates Chart
Fractional Flow Charts
Prediction Results - Table
Oil Production
Display Historical Rate
Oil Production
Water Production
Liquids Production
Water Injection
Oil Production Rate
Cumulative Oil Production
40000
20000
0
100
80
60
40
20
0
01/01/2004
01/01/2008
01/01/2012
01/01/2016
01/01/2020
History
Rate
Capacity
Cumulative
Close


Analytical Relative Permeability
Fractional Flow
Welge Displacement
History Match
Prediction
Prediction Setup
Rates Chart
Fractional Flow Charts
Prediction Results - Table
Water Production
Display Historical Rate
Water Production Rate
Cumulative Water Production
60000
40000
20000
0
350
300
250
200
150
100
50
0
01/01/2004
01/01/2008
01/01/2012
01/01/2016
01/01/2020
History
Rate
Capacity
Cumulative
Close

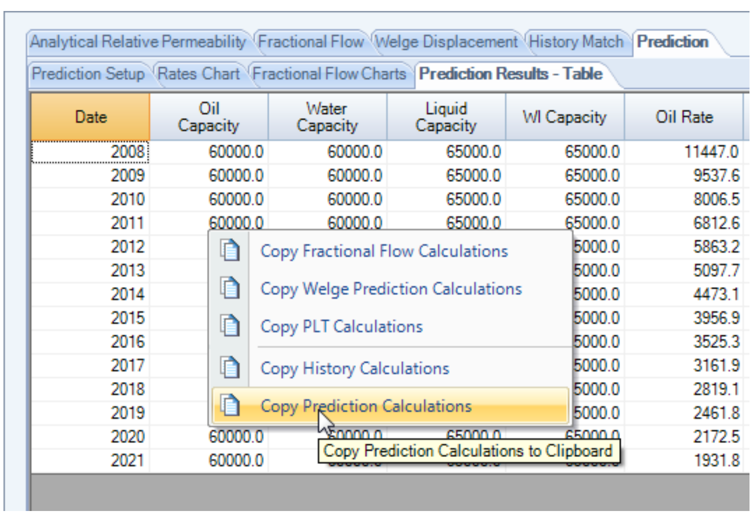

Analytical Relative Permeability
Fractional Flow
Welge Displacement
History Match
Prediction
Prediction Setup
Rates Chart
Fractional Flow Charts
Prediction Results - Table
Npd v's fws
Npd v's fws
Swe v's fwe
fws [fraction]
0.00
0.20
0.40
0.60
0.80
0.00
0.20
0.40
0.60
0.80
1.00
Npd [fraction]
History
Layer Calculation
Prediction
Close


Analytical Relative Permeability
Fractional Flow
Welge Displacement
History Match
Prediction
Prediction Setup
Rates Chart
Fractional Flow Charts
Prediction Results - Table
Swe v's fwe
1.00
0.80
0.60
0.40
0.20
0.00
fwe [fraction]
0.00
0.20
0.40
0.60
0.80
1.00
Swe [fraction]
History
Layer Calculation
Prediction
Close



Date	Oil Capacity	Water Capacity	Liquid Capacity	WI Capacity	Oil Rate	Water Rate	Liquid Rate	WI Rate	Watercut	Cumulative Oil
2008	60000.0	60000.0	65000.0	65000.0	11447.0	46714.3	58161.3	65000.0	0.803185	59.5264
2009	60000.0	60000.0	65000.0	65000.0	9537.6	49448.6	58986.2	65000.0	0.838309	63.0077
2010	60000.0	60000.0	65000.0	65000.0	8006.5	51641.2	59647.7	65000.0	0.865771	65.9300
2011	60000.0	60000.0	65000.0	65000.0	6812.6	53350.9	60163.5	65000.0	0.886766	68.4166
2012	60000.0	60000.0	65000.0	65000.0	5863.2	54710.5	60573.7	65000.0	0.903206	70.5625
2013	60000.0	60000.0	65000.0	65000.0	5097.7	55806.6	60904.4	65000.0	0.916299	72.4232
2014	60000.0	60000.0	65000.0	65000.0	4473.1	56701.1	61174.2	65000.0	0.926879	74.0559
2015	60000.0	60000.0	65000.0	65000.0	3956.9	57440.4	61397.3	65000.0	0.935553	75.5001
2016	60000.0	60000.0	65000.0	65000.0	3525.3	58058.5	61583.7	65000.0	0.942756	76.7904
2017	60000.0	60000.0	65000.0	65000.0	3161.9	58578.9	61740.7	65000.0	0.948788	77.9445
2018	60000.0	60000.0	65000.0	65000.0	2819.1	59069.7	61888.8	65000.0	0.954449	78.9735
2019	60000.0	60000.0	65000.0	65000.0	2461.8	59581.4	62043.2	65000.0	0.960322	79.8720
2020	60000.0	60000.0	65000.0	65000.0	2172.5	59950.7	62123.2	64953.6	0.965029	80.6671
2021	60000.0	60000.0	65000.0	65000.0	1931.8	60000.0	61931.9	64649.5	0.968807	81.3723

The user can copy any of the data to the Windows clipboard from any of the tables by either, clicking and dragging an area with their mouse and pressing CTRL+C, then pasting into an external application, or when the mouse is over a active table single right click the mouse to display the tables context menu then select the table that requires to be copied. The benefits of selecting the second approach over the first approach is that the table headers will also be be copied to the clipboard. See screen capture below.



References:

Fassihi, M., “New Correlations for Calculation of Vertical Coverage and Areal Sweep Efficiency,” *SPERE,* Nov. 1986

2.3 Reverse Welge

Within the Waterdrive chapter of Dake's "The Practice of Reservoir Engineering", he presents a technique for examining and interpreting the waterdrive performance of reservoirs or numerical simulation models from inspection of their historic production/injection records. Extracts from this chapter as used to outline this technique.

"This approach to understanding the reservoir mechanics of a waterflood relies on the development of an underground fractional flow of water by solving the Welge equation in reverse. That is, for an observed set of production statistics: Np, Wi, fws, converted to their reservoir equivalents of Npd, Wid, fwe, the following equation is solved for Swe, thus establishing the fractional flow relationship: fwe versus Swe.

$$N_{pd} = \left(S_{we} - S_{wc}\right) + \left(1 - f_{we}\right) W_{id}$$

In this respect the reservoir or model, no matter how complex it may be: containing numerous vertical/ horizontal wells, fractures or heterogeneity, is simply viewed as a Buckley-Leverett "black-box", in which the injection, qwi, and production, qo + qwp, are linked together by the fractional flow relationship."

The associated equations for Npd, Wid and fwe are included for completeness.

$$N_{pd} = \frac{N_p B_o}{N B_{oi}} \left(1 - S_{wc}\right)$$

$$W_{id} = \frac{W_i}{N B_{oi}} \left(1 - S_{wc}\right)$$

$$f_{we} = \frac{1}{1 + \frac{B_o}{B_w}\left(\frac{1}{f_{ws}} - 1\right)}$$

In solving the Welge equation for Swe, for values of Npd, Wid and fwe, it is assumed that the reservoir or simulator obeys Buckley-Leverett mechanics. Consequently, a fractional flow (fwe versus Swe) is obtained for which the extrapolation of the final points to the line fwe = 1 gives the value of Swbar, the average saturation in the "black-box", at that stage of the flood from which the oil recovery can be determined from :

$$N_{pd} = \overline{S}_w - S_{wc}$$

and the reciprocal of the tangent of this extrapolation gives the cumulative water injection required to attain the recovery as :

$$W_{id} = 1 \Bigg/ \left(\frac{\Delta f_{we}}{\Delta S_{we}} \right)$$

Linking the above two equations with the underground material balance for waterdrive under pressure maintenance conditions, included immediately below, allows the forward calculation of production and injection profiles for a given set of facilities constraints.

$$q_{wi} = q_o B_o + q_{wp} B_w$$

$$f_{ws} = \frac{q_{wp}}{q_o + q_{wp}}$$

Integrating the above two equations, results in the following :

$$q_{wi} = q_o \left(B_o + \frac{B_w f_{ws}}{1 - f_{ws}} \right)$$

where,
qwi = water injection capacity
qo = oil processing capacity
qo + qwp = total separation capacity
qwp = water disposal capacity

The above techniques are outlined in more detail in the following example.

References:

Dake, L., *"The Practice of Reservoir Engineering",* Elsevier Scientific Publishing Company, 1994.

Welge, H.J., *"Predicting Displacement Efficiency From Water-cut or Gas-Cut Field Data"*, SPE Paper 5313, 1975

Welge, H.J., "*A Simplified Method for Computing Oil Recovery By Gas or Water Drive",* Trans. AIME*,* 1952,

2.3.1 Example

Dake provides an example (Example 5.23) in his waterdrive chapter of "The Practice of Reservoir Engineering", which will be used, albeit somewhat modified, to outline this routine in more detail.

Input Data

STOOIP [mmstb]	126
Initial Oil FVF, Boi [rb/stb]	1.29
Current Oil FVF, Bo [rb/stb]	1.29
Water FVF, Bw [rb/stb]	1
Swc, fraction	0.26
Sor, fraction	0.32

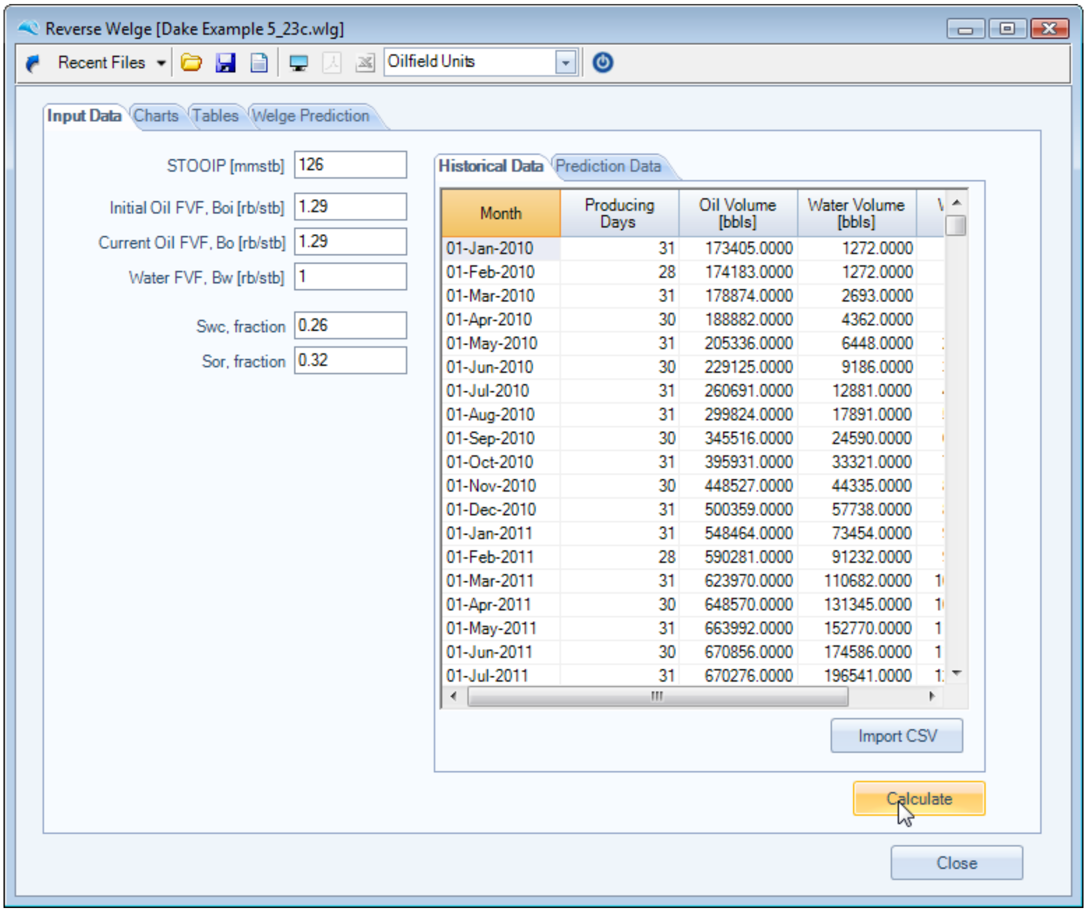
Year	Np [mmstb]	Wi [mmstb]	fws
1	3.4	4.9	0.128
2	11	18.9	0.356
3	16.9	36.6	0.631
4	21.4	55.7	0.747
5	24.9	73.7	0.794
6	28	92.6	0.828
7	30.5	111	0.859
8	32.8	130.3	0.876
9	34.8	149.2	0.891
10	36.6	168.5	0.904
11	38.1	187.5	0.919
12	39.5	206.9	0.926
13	40.7	224.3	0.93
14	41.8	242.2	0.938
15	42.7	257.9	0.942
16	43.6	274	0.943
17	44.4	290.1	0.949
18	45.2	305.4	0.947
19	45.9	321.1	0.955
20	46.6	337.6	0.957

Problem Statement

For the above production history, calculate :

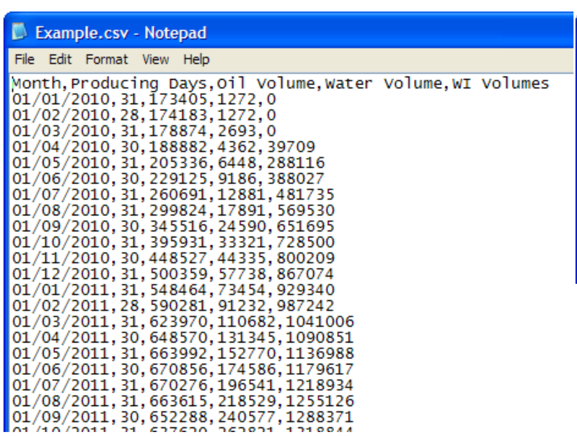
1. the incremental oil production rate in year 21 assuming the water injection system is upgraded from is it's current level of 45,000 bwpd to 80,000 bwpd,
2. the remaining oil production to an abandonment watercut of 99.9%
3. The number of years required to reach the abandonment watercut of 99% for both the 45,000 bwpd to 80,000 bwpd levels.

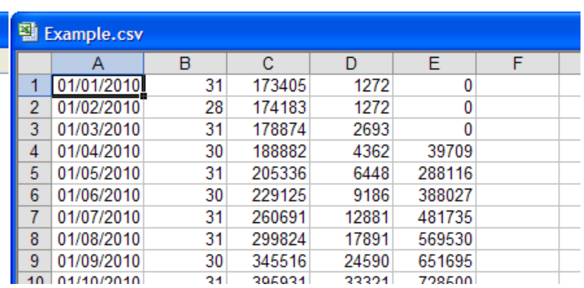
In this example, the yearly production data has been spline curve fitted to allow the data to be input as monthly data, and formatted into the correct input units. See input screen below.



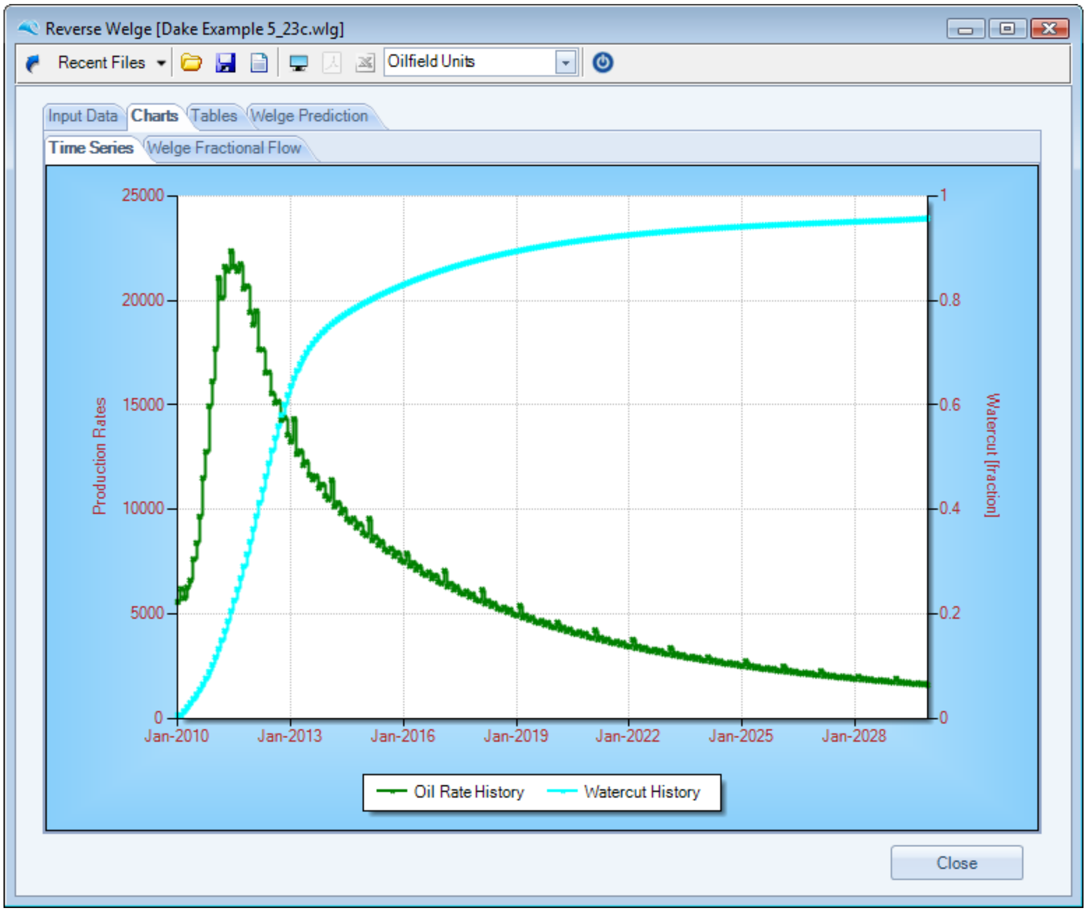
Note that the monthly production and injection history, as per the format shown above, can be input either by importing via a comma delimited ASCII file and by pressing the Import CSV button, or be copied and pasted into the input table by pressing the windows standard shortcut keys [CTRL+C] then [CTRL+V].

Example formats of comma delimited ASCII file (CSV) file are shown below.

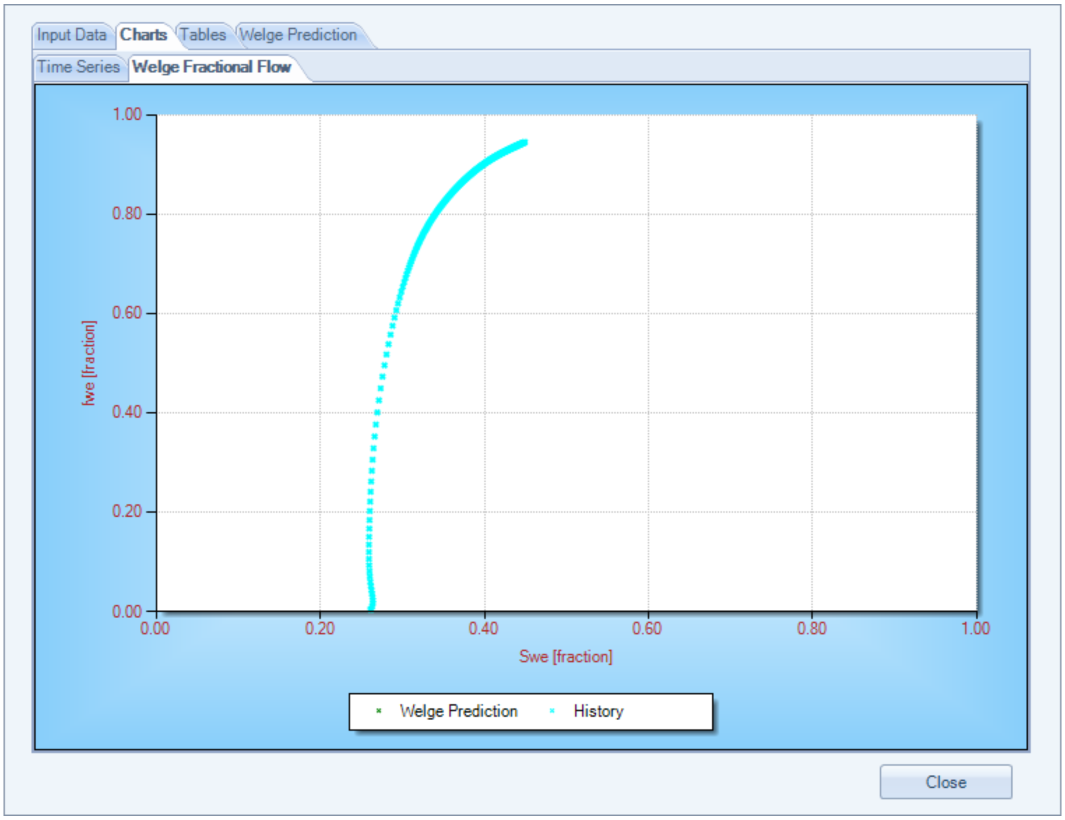




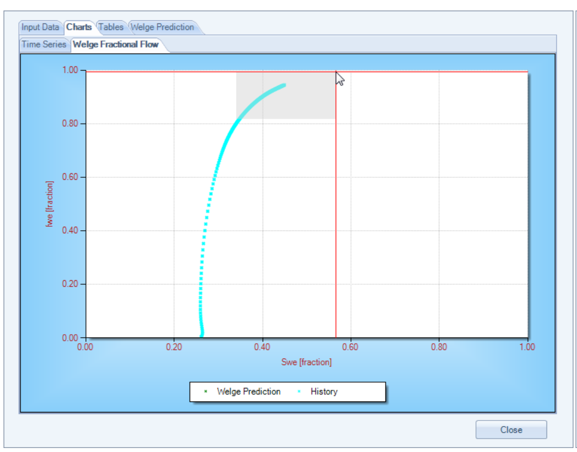
Once the user is happy with the input data they should press the *Calculate* button, and the following charts and tables should be displayed.

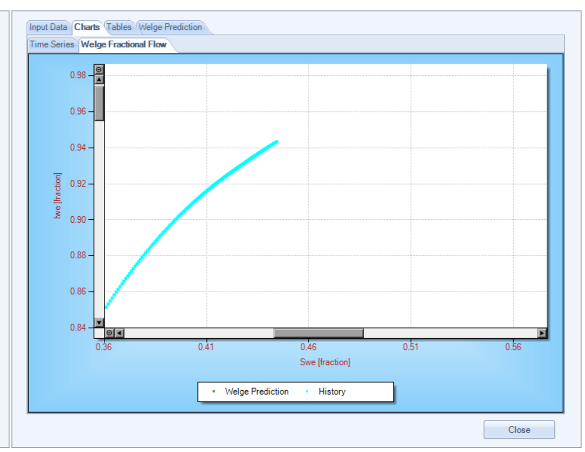


The following chart is the production and injection history data converted to a Welge fractional flow.

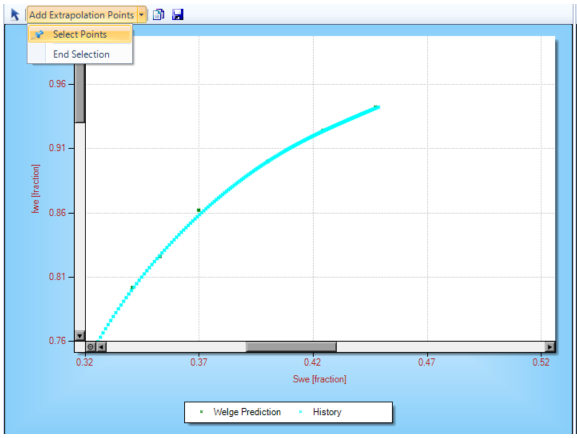


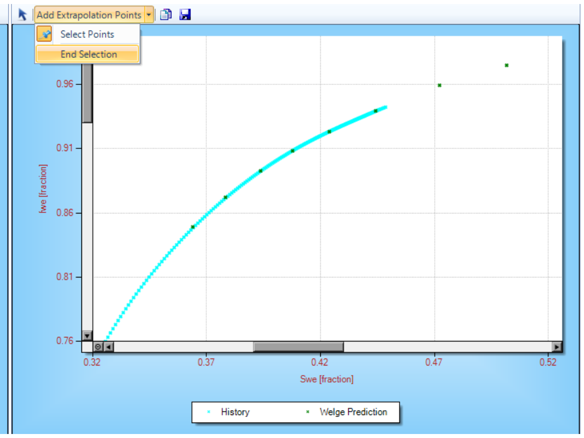
The user can zoom into the late time data to better digitize extrapolation points. To zoom click and drag the left mouse button for the required zoom area. To unzoom press the small icons located in the top of the y-axis scrollbar or at the left edge of the x-axis scrollbar.



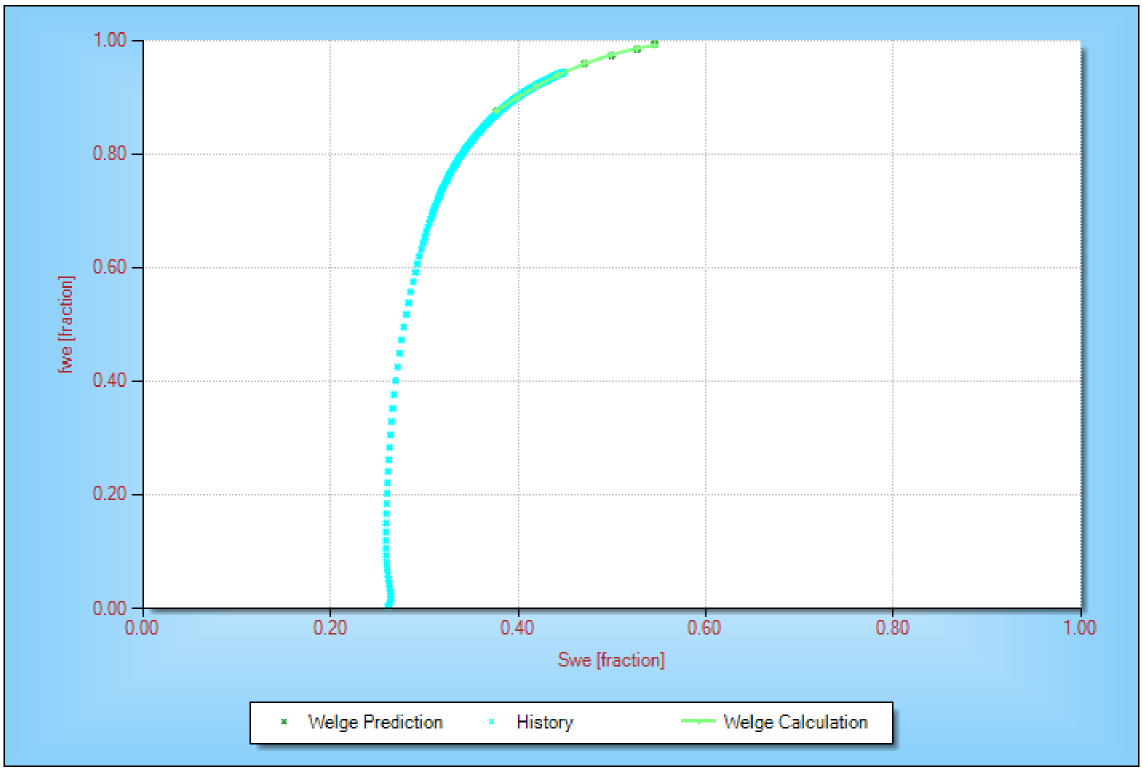


To select extrapolation to digitize, highlight the chart's context menu list by pressing the right mouse button whilst anywhere within the chart area. Then select the "Add Extrapolation Points" & "Select Points", as shown below. Then simply left mouse click where you want to add digitized points. Once the user is happy with the number and location of digitized points, select an area within the margins of the chart (ie,. not in the data display area), and again pressing the right mouse button, select "Add Extrapolation Points" & "End Selection", as shown below.





The following should be displayed. *Although some automatic re-zooming may take place, which may require manually unzooming and re-zooming into the area of interest with the chart*.



Once the user is happy with the fractional flow extrapolation that have been digitized and curve fitted, they should select the "Welge Prediction" TAB, as shown below.

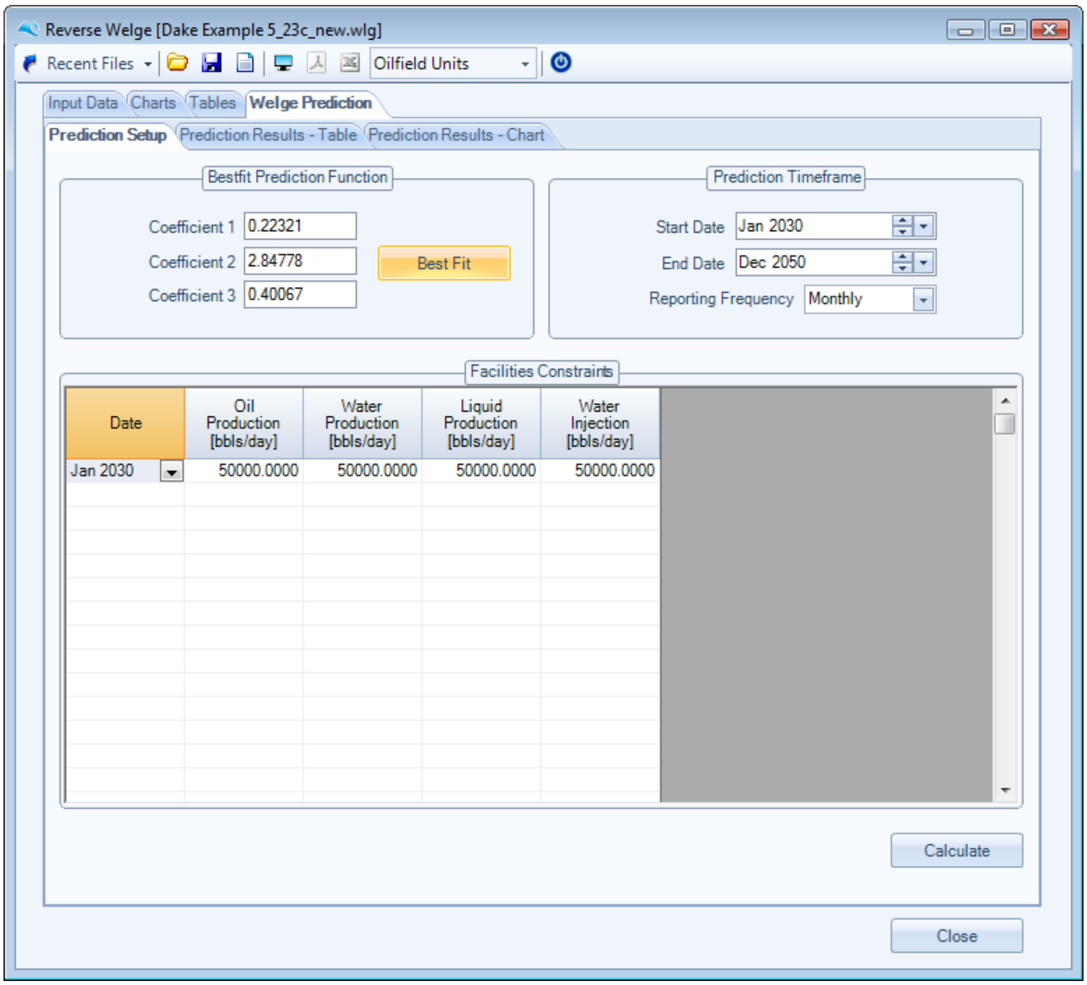
Within this TAB the user can input a prediction timeframe, facilities constraints and a bestfit prediction function.

The ***Bestfit Prediction Function*** returns the coefficients (C1, C2 and C3) of the following equation :

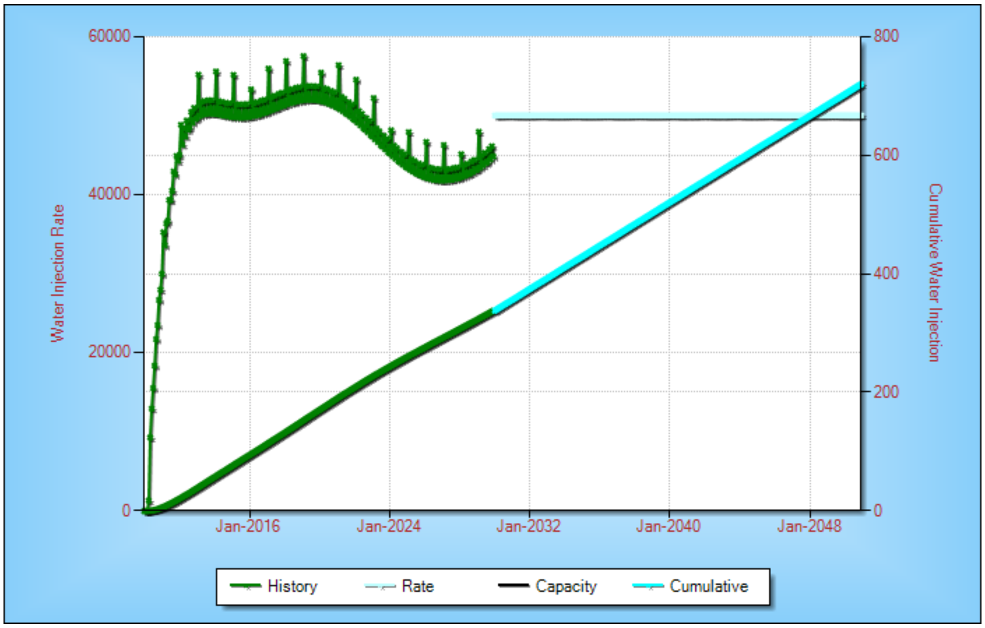
$$f_{we} = \left(1 + C_1.\left[\frac{(1-E_D)^{C_2}}{{E_D}^{C_3}}\right]\right)^{-1}$$

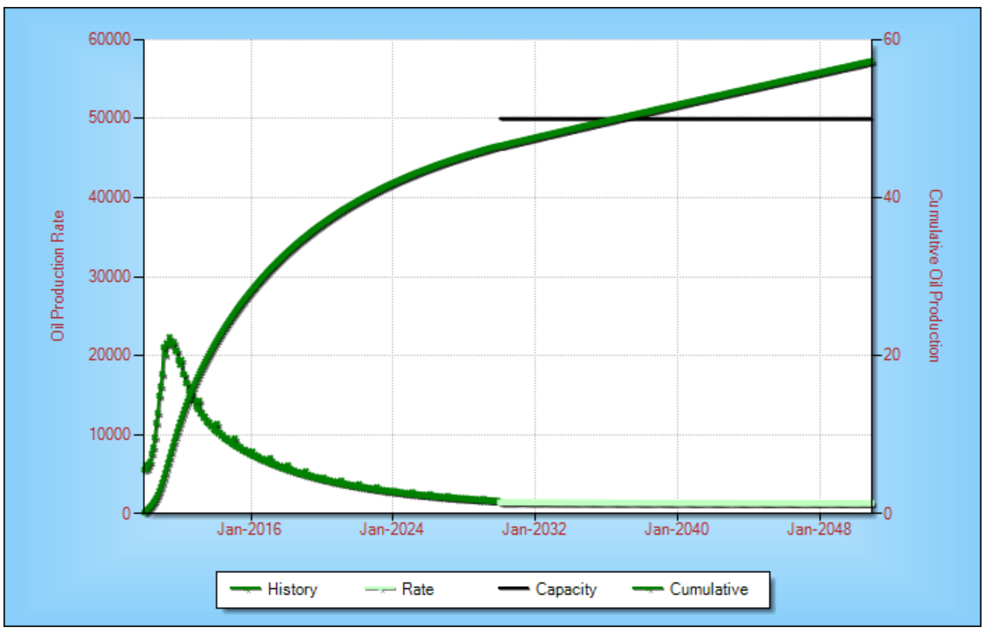
where Ed is the microscopic displacement efficiency, given by the following formula :

$$E_D = \frac{Sw - Sw_c}{1 - Sw_c - So_r}$$



Once the user presses the *Calculate* button, as shown above, the Welge prediction is performed, for the selected timeframe, using the curve fitted fractional flow extrapolation and the facilities constraints. In this example, for the 45,000 bwpd injection case, the following two screen captures show the predicted water injection and oil production profiles.

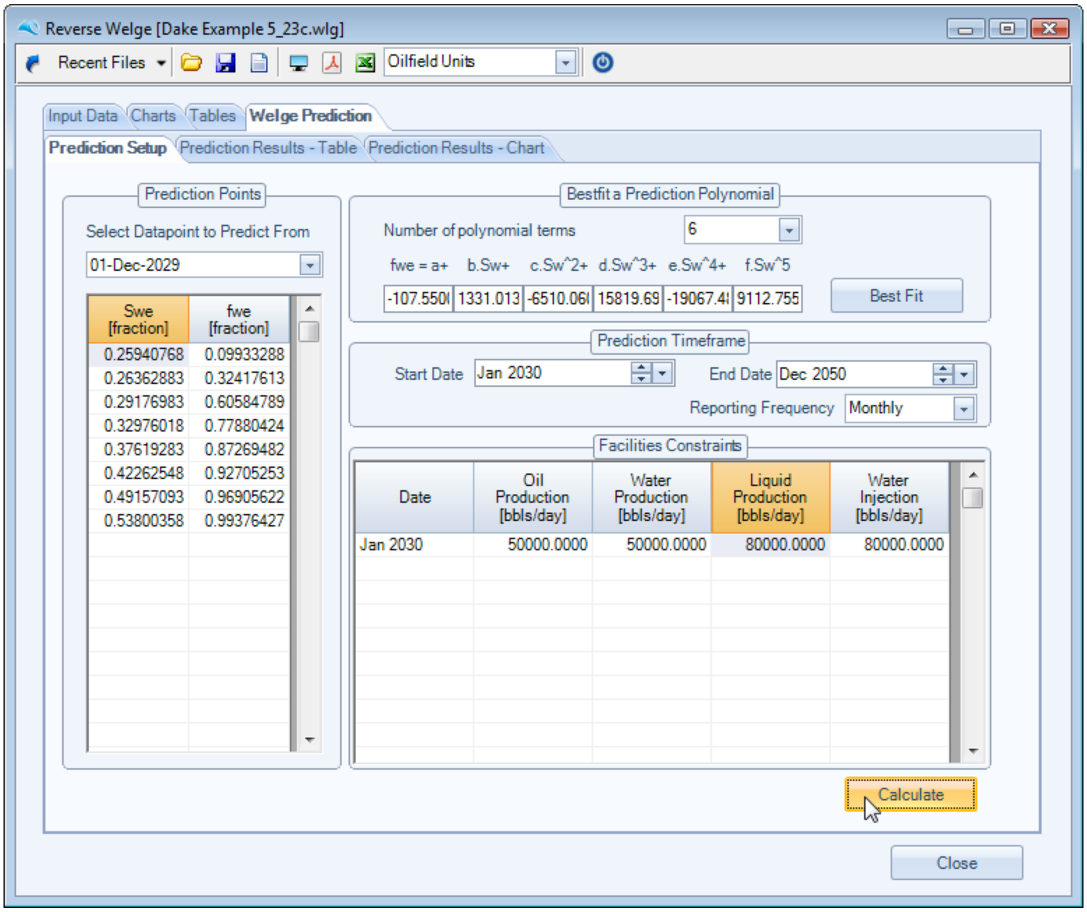




From the above, the prediction is constrained throughout the prediction period by water injection, and the oil production profile appears to merge with history and extrapolate well.

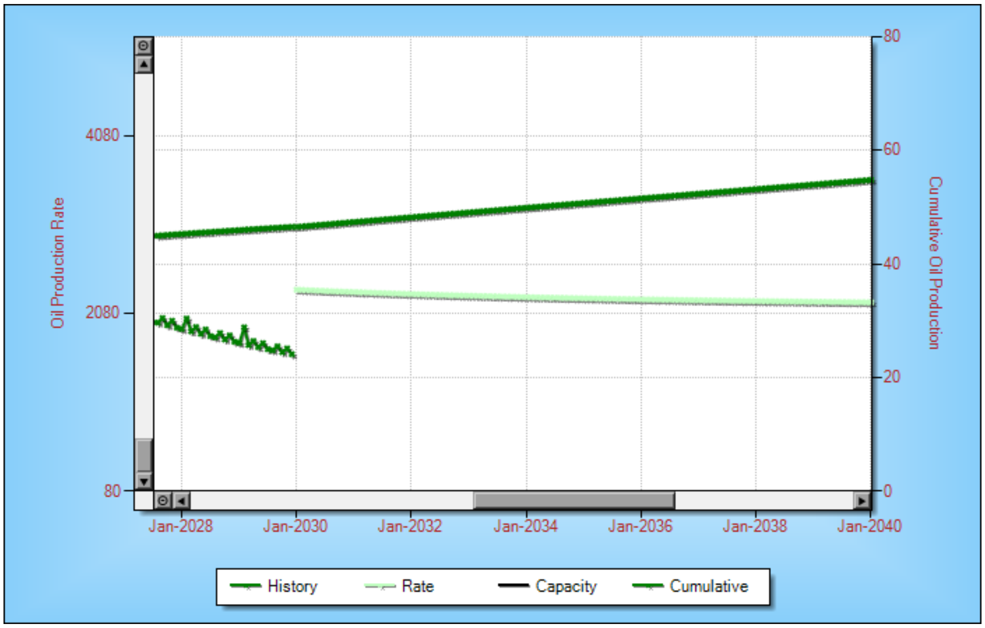
The calculated initial oil rate in year 21 is approximately 2200 bopd, and the ultimate recovery predicted at abandonment watercut is 50.5 mmstb. A remaining reserve figure of 3.9 mmstb,

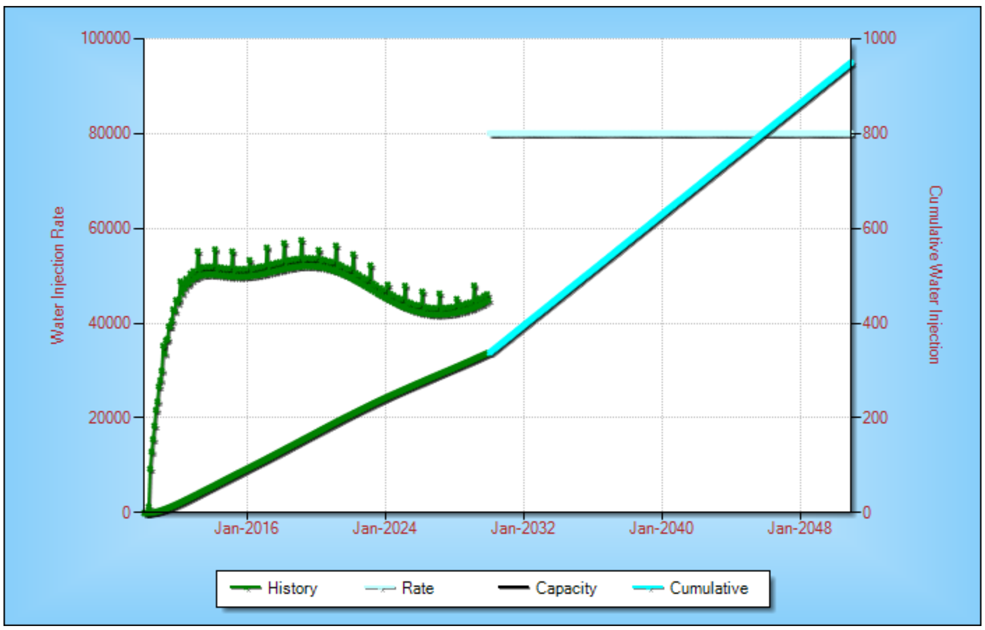
To quantify the incremental oil production rate for upgrading the water injection capacity to 80,000 bwpd is shown in the following screen captures. The user simplys input the 80,000 bpd for water injection (and water and liquid production, since this will be the next constraint to be met in the prediction calculations) and again presses the *Calculate* button.



The results for the 80,000 bwpd case are shown below. From these calculations, the oil rate predicted initially in year 21 is approximately 2300 bopd, an incremental oil rate of 600 bopd over the 45,000 bwpd injection case. The 80,000 bwpd injection case also reaches 50.5 mmstb ultimate recovery, but 5 years earlier.

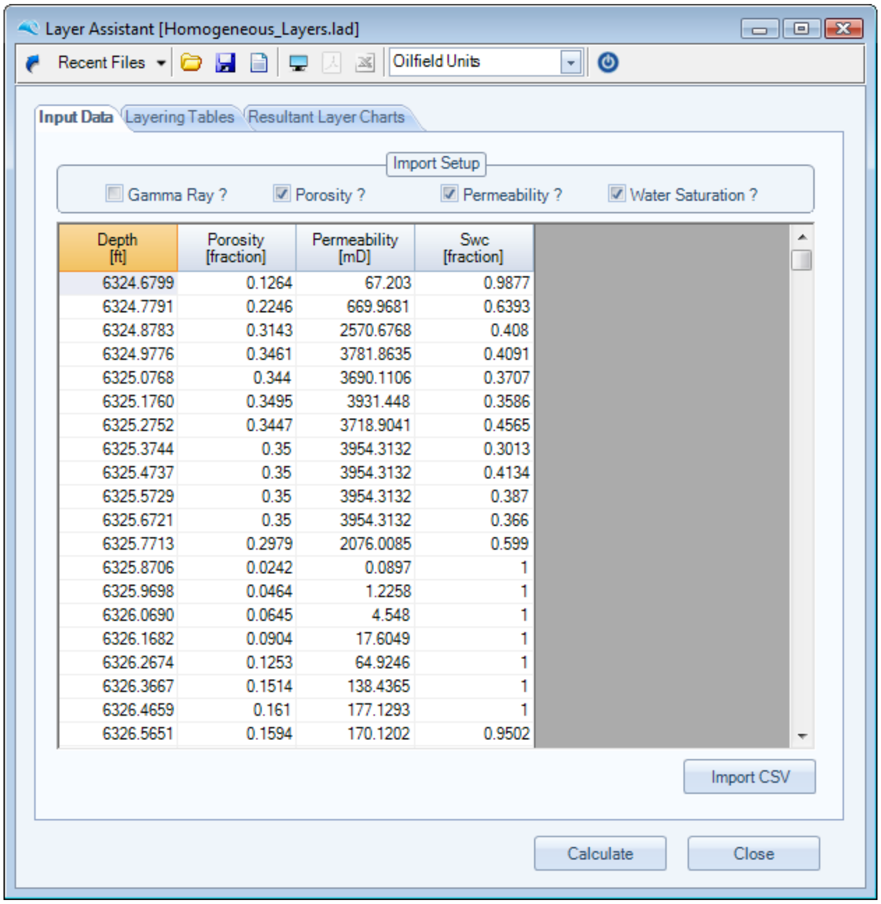
Obviously the additional capital expenditure required to upgrade injection capacity may be more than offset by the acceleration of oil production and the saving of 5 years field operating expenditure.





2.4 Layer Assistant

A simple Log Value Layering tool is provided to quickly sub divide either Gamma ray, Porosity, Permeability or Water saturation logs into a discrete series of layers for use in the Multi Layer Fractional Flow Model or Craig-Geffen-Morse Layer model.

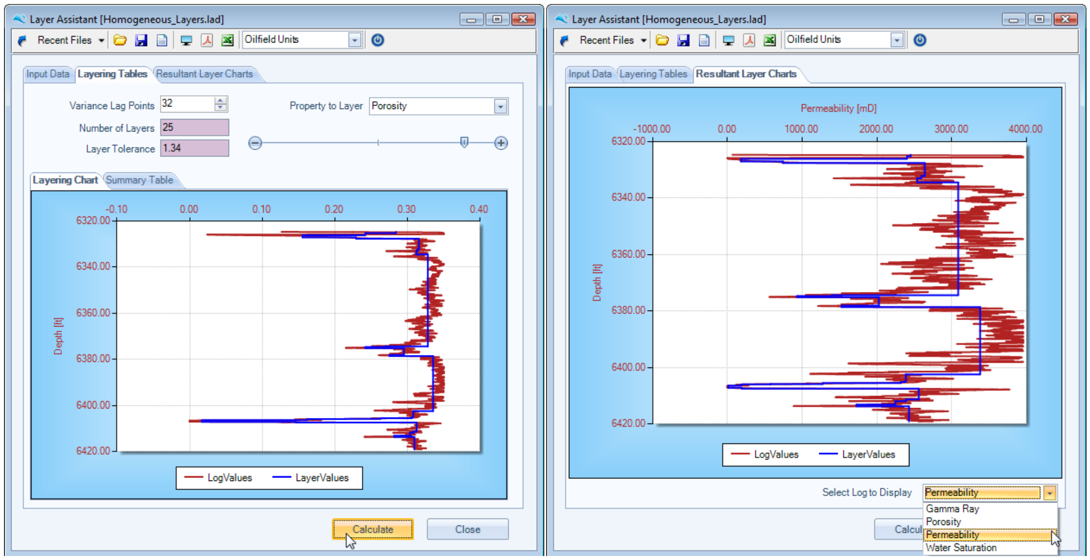


Either copy and paste the log data directly into the input data grid shown above, or use the Import CSV button to import an ASCII comma delimited file into this data grid. It is important to note that the structure of the CSV file must contain 5 columns of data even if the 5 columns are not used (column 1 = depth, column 2 = GR, column 3 = Porosity, column 4 = Permeability, column 5 = Swc). In the instance where the log data is not used simply enter 0 values for the entire column of values.

For the example shown above the top line of the CSV would look like ; 6324.6799, 0, 0.1264, 67.203, 0.9877.

Then select the "Layering Tables" tab, as shown below, input the required Variance Lag points [default value is set to 10], then select the log in which to calculate the numbers of layers, and press the Calculate button. Once the Calculation has been performed the log and layer values should be shown in the Layering Chart and Summary Table. The user can quickly change the character of the layering by iterating with both the Layer Tolerance slider bar and the Variance Lag points.

Once the user is happy with the layering calculations, they can choose to display other logs and layer averages in the final tab "Resultant Layer Charts", as shown in the right hand image below.


Layer Assistant [Homogeneous_Layers.lad]
Recent Files
Oilfield Units
Input Data
Layering Tables
Resultant Layer Charts
Variance Lag Points
32
Property to Layer
Porosity
Number of Layers
25
Layer Tolerance
1.34
Layering Chart
Summary Table
Depth [ft]
LogValues
LayerValues
Calculate
Close
Layer Assistant [Homogeneous_Layers.lad]
Permeability [mD]
Select Log to Display
Permeability
Gamma Ray
Porosity
Permeability
Water Saturation

Part III

3 Craig

Forest Craig's SPE Monograph ***"The Reservoir Engineering Aspects of Waterflooding"***, first published in 1971, is referenced in practically all text books and technical papers associated with waterdrive and water flooding literature.

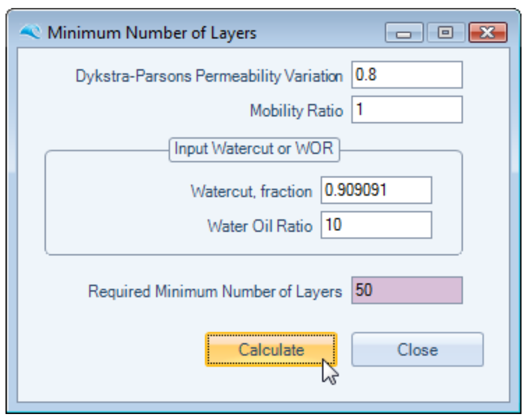
His techniques, presented within this textbook, form the basis for the routines contained within this section.

3.1 Craig's Minimum Number of Layers

Craig outlined guidelines for selecting the minimum number of layers needed to predict the performance of a reservoir under waterflooding operation. The author simulated the performance of a waterflood five-spot pattern that is composed of 100 layers with permeability variations ranging from 0.4 to 0.8. The minimum number of layers required to match results of the 100-layer model was determined as a function of mobility ratio and permeability variation.

His guidelines are the basis for this routine.

To calculate the minimum number of layers from Craig's data, simply enter the Dykstra-Parsons Permeability Variation, the Mobility Ratio and the WOR limit to be modelled, as shown below.



References:

Craig, Jr., F., *"The Reservoir Engineering Aspects of Waterflooding"*, Society of Petroleum Engineers, 1971

3.2 Craig-Geffen-Morse Recovery Performance

3.2.1 Introduction

To obtain waterflood performance with time for a five-spot pattern the approach of Craig, Geffen, and Morse for relating oil recovery and producing WOR to cumulative injected water is coupled with the correlation of Caudle and Witte for calculating five-spot water injection rates.

This method of predicting five-spot water injection performance is valid either with or without free gas present, provided that there is no trapped gas behind the flood front. The calculations, however, are not valid for floods in which there is bottom water present.

These calculations assume a vertical sweep efficiency of 100 percent in each layer, ie., the fluids are not segregated by gravity.

For stratified reservoirs with layers of different water-oil relative permeability characteristics, the performance of each layer must be calculated individually.

The performance of a waterflood can be divided into four stages.

1.	Start to Interference	The period of radial flow out from the injectors from the start of injection until the oil banks, formed around adjacent injectors, meet. The meeting of adjacent oil banks is termed "interference".
2.	Interference to Fillup	The period from interference until fillup of the pre-existing gas space. Fillup is the start of oil production response.
3.	Fillup to Water Breakthrough	The period from fillup to w ater breakthrough at the producing w ells. Breakthrough marks the beginning of w ater production.
4.	Post Water Breakthrough	The period from w ater breakthrough to floodout.

For a multi layered system, Craig proposed performing the calculations for one selected layer, identified as the ***base layer***. The performance of each of the remaining layers is obtained by “sliding the timescale”, and summing the individual layer performance variables to calculate the composite multi layer performance. See Composite Layer Performance.

References:

Craig, Jr., F., *"The Reservoir Engineering Aspects of Waterflooding"*, Society of Petroleum Engineers, 1971

Craig, F., Geffen, T., and Morse, R., “*Oil Recovery Performance of Pattern Gas or Water Injection Operations from Model Tests*” JPT*,* Jan. 1955

Caudle, B., and Witte, M., “*Production Potential Changes During Sweep-out in a Five-Spot System*” AIME, 1959, Vol. 216

Ahmed, T., “*Reservoir Engineering Handbook*”, Elsevier, 2006

3.2.2 Start to Interference

This is a period of radial flow out from the injectors from the start of injection until the oil banks, formed around adjacent injectors, meet. The meeting of these adjacent oil banks is termed "interference".

The performance calculations, for this stage, are given by the two following steps:

1. Calculate the cumulative water injected to interference from the following equation :

$$W_{ii} = \frac{\pi . h . \phi . S_{gi} . r_{ei}^{2}}{5.615}$$

where,
Wii = cumulative water injected to interference

Sgi = initial gas saturation
ϕ = porosity
rei = half the distance between adjacent injectors

2. Assume successive values of cumulative water injected, ranging between 0 and Wii, and calculate the water-injection
rate from the following equation :

$$i_w = \frac{0.00707.k.h.\Delta P}{\left(\frac{\mu_w}{k_{rw}}.\ln\left(r/r_w\right) + \frac{\mu_o}{k_{ro}}.\ln\left(r_o/r\right)\right)}$$

where,
iw = water injection rate
ΔP = pressure difference between injector and producer
k = absolute permeability, md
kro = relative permeability of oil at Swi
krw = relative permeability of water at SwBT
ro = outer radius of the oil bank
r = outer radius of the water bank
rw = wellbore radius

The outer radii of the oil and water banks are calculated from the following equations :

$$r_o = \sqrt{\frac{5.615.W_{inj}}{\pi.h.\phi.S_{gi}}} \qquad r = r_o\sqrt{\frac{S_{gi}}{\overline{S}_{wBT} - S_{wi}}}$$

3.2.3 Interference to Fillup

This is the period from interference until fill up of the pre-existing gas space.

Fill-up is marked by the following four events :

1. No free gas remaining in the flood pattern
2. Arrival of the oil-bank front to the production well
3. Flood pattern response to the waterflooding
4. Oil flow rate equal to the water injection rate

The performance calculations, for this stage, are given by the following steps:

1. Calculate the cumulative water injected at fill-up by applying the following equation :

$$W_{if} = PV.S_{gi}$$

where,
Wif = cumulative water injected at fill-up

PV = total flood pattern pore volume
Sgi = initial gas saturation

2. Calculate the areal sweep efficiency at fill-up by using the following equation :

$$E_A = \frac{W_{inj}}{PV.\left(\overline{S}_{wBT} - S_{wi}\right)}$$

3. Using the mobility ratio and the areal sweep efficiency at fill-up, determine the conductance ratio from the following equation :

$$\gamma = a_1 + \left(a_2 + a_3.E_A\right).M^{\left(a_4 + a_5.E_A\right)} + a_6.\left(\frac{M}{E_A}\right)^2 + a_7.M$$

where,
a1 to a7 are coefficients based on mobility ratio.
also, for an areal sweep efficiency of 100%, the conductance ratio equals the mobility ratio.

4. For a constant pressure difference, the initial (base) water injection rate is given by the following equation :

$$i_{base} = \frac{0.003541.h.k.k_{ro}\Delta P}{\mu_o\left[\ln\left(\frac{d}{r_w}\right) - 0.619\right]}$$

5. Calculate the water injection at fill-up from the following equation :

$$i_{wf} = \gamma.i_{base}$$

6. Calculate the incremental time occurring from interference to fill-up from the following equation :

$$\Delta t = \frac{W_{if} - W_{ii}}{\left(\frac{\left(i_{wi} + i_{wf}\right)}{2}\right)}$$

3.2.4 Fillup to Water Breakthrough

This is the period from fillup to water breakthrough at the producing wells.

During this stage, the oil production rate is essentially equal to the injection due to the fact that no free gas exists in the swept flood area. With continuous water injection, the leading edge of the water bank eventually reaches the production well, and marks the time to water breakthrough.

The performance calculations, for this stage, are given by the following steps:

1. Calculate cumulative water injected at breakthrough by using the following equation :

$$W_{iBT} = PV.\left(\overline{S}_{wBT} - S_{wi}\right).E_{ABT}$$

2. Assume several values of cumulative water injected between Wif and WiBT and calculate the areal sweep efficiency at each value, using the following equation :

$$E_A = \frac{W_{inj}}{PV.\left(\overline{S}_{wBT} - S_{wi}\right)}$$

3. Calculate the conductance ratio γ for each assumed value of Winj, again from the following equation :

$$\gamma = a_1 + \left(a_2 + a_3.E_A\right).M^{\left(a_4 + a_5.E_A\right)} + a_6.\left(\frac{M}{E_A}\right)^2 + a_7.M$$

where,
a1 to a7 are coefficients based on mobility ratio.
also, for an areal sweep efficiency of 100%, the conductance ratio equals the mobility ratio.

4. Calculate the water injection rate at each Winj step, from the following :

$$i_w = \gamma.i_{base}$$

5. Calculate the oil flow rate during this stage from :

$$q_o = \frac{i_w}{B_o}$$

6. And finally, calculate the cumulative oil production from the following :

$$N_p = \frac{W_{inj} - W_{if}}{B_o}$$

3.2.5 Post Water Breakthrough

This is the period from water breakthrough to floodout.

After breakthrough, the water–oil ratio increases with a subsequent decline in the oil flow rate. The swept area will continue to increase as additional water is injected. The incrementally swept area will contribute additional oil production, while the previously swept area will continue to produce both oil and water.

The performance calculations, for this stage, are given by the following steps:

1. Assume several values for the ratio Winj/WiBT and calculate the cumulative water injected for each ratio from the following

$$W_{inj} = \left(\frac{W_{inj}}{W_{iBT}}\right).W_{iBT}$$

2. Calculate the areal sweep efficiency at each assumed ratio from the following equation :

$$E_A = E_{ABT} + 0.633.\log\left(\frac{W_{inj}}{W_{iBT}}\right)$$

3. Calculate the ratio Qi/QiBT that corresponds to each value of Winj/WiBT using the following equation :

$$\frac{Q_i}{Q_{iBT}} = 1 + a_1.e^{-a_1}\left[Ei(a_2) - Ei(a_1)\right]$$

where,

$$a_1 = 3.65.E_{ABT} \qquad a_2 = a_1 + \ln\left(\frac{W_{inj}}{W_{iBT}}\right)$$

and Ei is the exponential integral function.

4. Determine the total pore volumes of water injected from the following :

$$Q_i = \left(\frac{Q_i}{Q_{iBT}}\right).Q_{iBT}$$

5. Calculate the slope dfw/dSw for each value of Qi from the following :

$$\left(\frac{df_w}{dS_w}\right)_{Sw2} = \frac{1}{Q_i}$$

6. Calculate the value of Sw2, the water saturation at the producing well, that corresponds to each value

of dfw/dSw.

7. Calculate the reservoir water cut at the producing well for each value of Sw2, from the following equation :

$$f_{w2} = \frac{1}{1 + \frac{\mu_w}{\mu_o} \cdot \frac{k_{ro}}{k_{rw}}}$$

8. Determine the average water saturation in the swept area, from the following :

$$\bar{S}_{w2} = S_{w2} + \frac{1 - f_{w2}}{\left(\frac{df_w}{dS_w}\right)_{S_{w2}}}$$

9. Calculate the surface water–oil ratio that corresponds to each value of fw2, from the following :

$$WOR_s = \frac{f_{w2}\left[1 - \Delta N_{p\_newly}\right]}{1 - f_{w2}\left[1 - \Delta N_{p\_newly}\right]}\left(\frac{B_o}{B_w}\right)$$

10. Calculate cumulative oil production incorporating for the oil lost to the unswept area of the flood pattern, from the following :

$$N_p = N_S.E_D.E_A - \frac{PV.(1 - E_A).S_{gi}}{B_o}$$

where,
E_D is the displacement efficiency, and is calculated from the following :

$$E_D = \frac{\bar{S}_w - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}}$$

11. Calculate cumulative water production from the following :

$$W_p = \frac{W_{inj} - N_p.B_o - PV.S_{gi}}{B_w}$$

12. Calculate krw at Sw2 and determine the mobility ratio M after breakthrough from the following :

$$M = \frac{k_{rw}@\bar{S}_{w2}}{k_{ro}@S_{wi}} \cdot \left(\frac{\mu_o}{\mu_w}\right)$$

13. Calculate the conductance ratio γ.

$$\gamma = a_1 + (a_2 + a_3.E_A).M^{(a_4 + a_5.E_A)} + a_6.\left(\frac{M}{E_A}\right)^2 + a_7.M$$

14. Calculate the water injection rate, from the following :

$$i_w = \gamma.i_{base}$$

15. And finally, calculate the oil and water production rates, from the following :

$$q_o = \frac{i_w}{B_o + B_w.WOR_s} \qquad q_w = q_o.WOR_s$$

3.2.6 Composite Layer Performance

To calculate the performance of all the other layers, in a multi layer reservoir that may differ in thickness, porosity, and permeability, the following calculation steps are applied.

1. Divide the reservoir into the required number of layers.
2. Calculate the performance of the base layer (layer n) from Start to Interference to Fillup to Water Breakthrough to End.
3. Obtain values of cumulative liquid volumes (NP, WP, Winj) and liquid rates (qo, qw , qw i) as a function of time t for the base layer (layer n).
4. For each layer, including the base layer n, calculate the follow ing : (k / f), (f . h) and (k . h)
5. For each reporting timestep, the follow ing is calculated for each layer i . Where, n = base layer, i = layer i, NP*, WP*, Winj* = volumes at t*, qo*, qw *, and qw i* =rates at t*

$$t_i^* = t\frac{\left(k/\phi\right)_i}{\left(k/\phi\right)_n} \quad N_p = N_p^*\frac{(\phi.h)_i}{(\phi.h)_n} \quad W_p = W_p^*\frac{(\phi.h)_i}{(\phi.h)_n} \quad W_{inj} = W_{inj}^*\frac{(\phi.h)_i}{(\phi.h)_n} \quad q_o = q_o^*\frac{(k.h)_i}{(k.h)_n} \quad q_w = q_w^*\frac{(k.h)_i}{(k.h)_n} \quad q_{wi} = q_{wi}^*\frac{(k.h)_i}{(k.h)_n}$$

6. The composite multi layer performance at each reporting timestep t is obtained by the summation of all the individual layer values.

The above calculation is only valid for reservoirs having equal initial gas saturation in each layer and insignificant producing rate prior to fillup.

3.2.7 Example

In Appendix E4 of Craig's "*The Reservoir Engineering Aspects of Waterflooding*", he presents the following example for calculating the Composite WOR Recovery Performance

General Input Data	
Oil viscosity [cP]	1
Water viscosity [cP]	0.5
Oil FVF, Bo [rb/stb]	1.2
Water FVF, Bw [rb/stb]	1
Residual Oil Saturation, Sor [fraction]	0.3
Initial Water Saturation, Swc [fraction]	0.1
Initial Gas Saturation, Sgi [fraction]	0.15

Injector wellbore radius [ft]	1
Pressure difference injector-producer [psi]	3000
Half distance between injectors [ft]	660
Distance injector to producer [ft]	932
Pattern Area, Acres	40
Base Layer Reservoir Thickness [ft]	5
Base Layer Permeability [mD]	31.5
Base Layer Porosity [fraction]	0.2

Relative Permeability Data

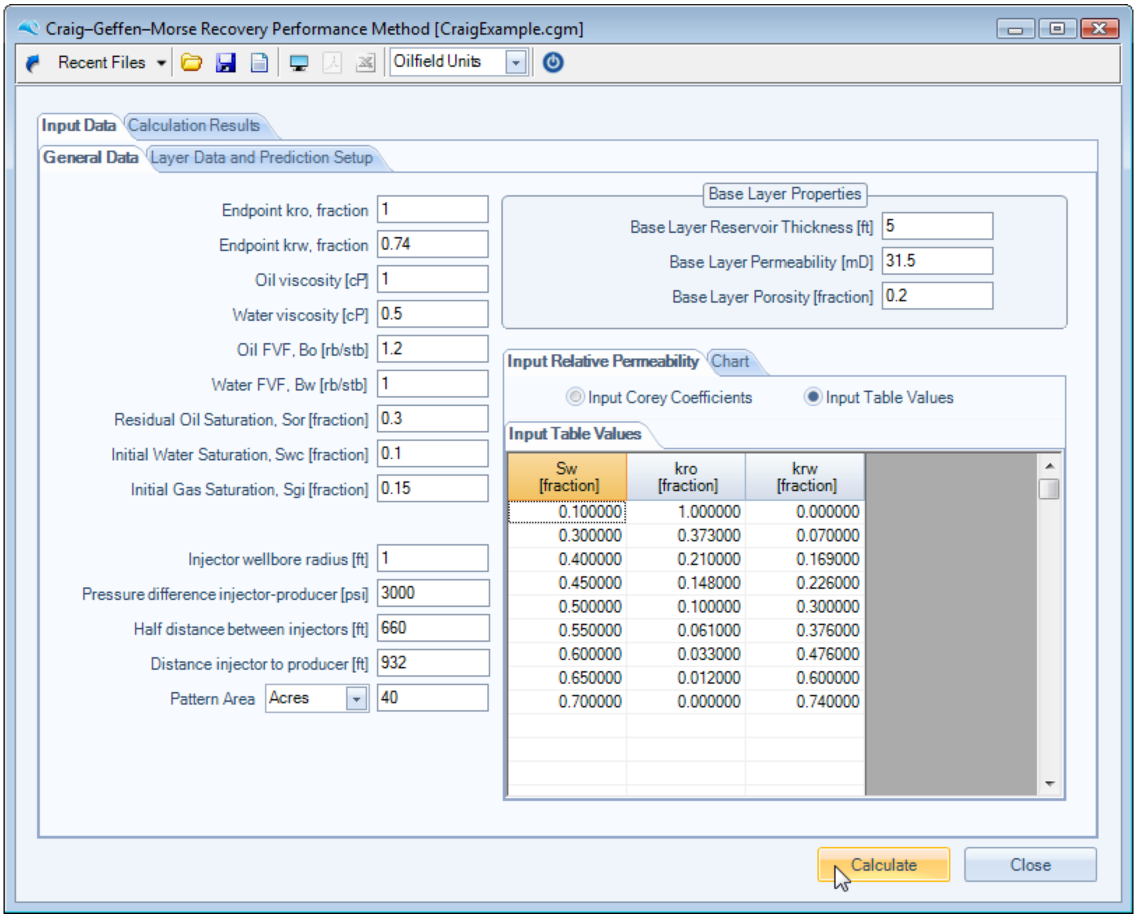
Sw	kro	krw
0.1	1	0
0.3	0.373	0.07
0.4	0.21	0.169
0.45	0.148	0.226
0.5	0.1	0.3
0.55	0.061	0.376
0.6	0.033	0.476
0.65	0.012	0.6
0.7	0	0.74

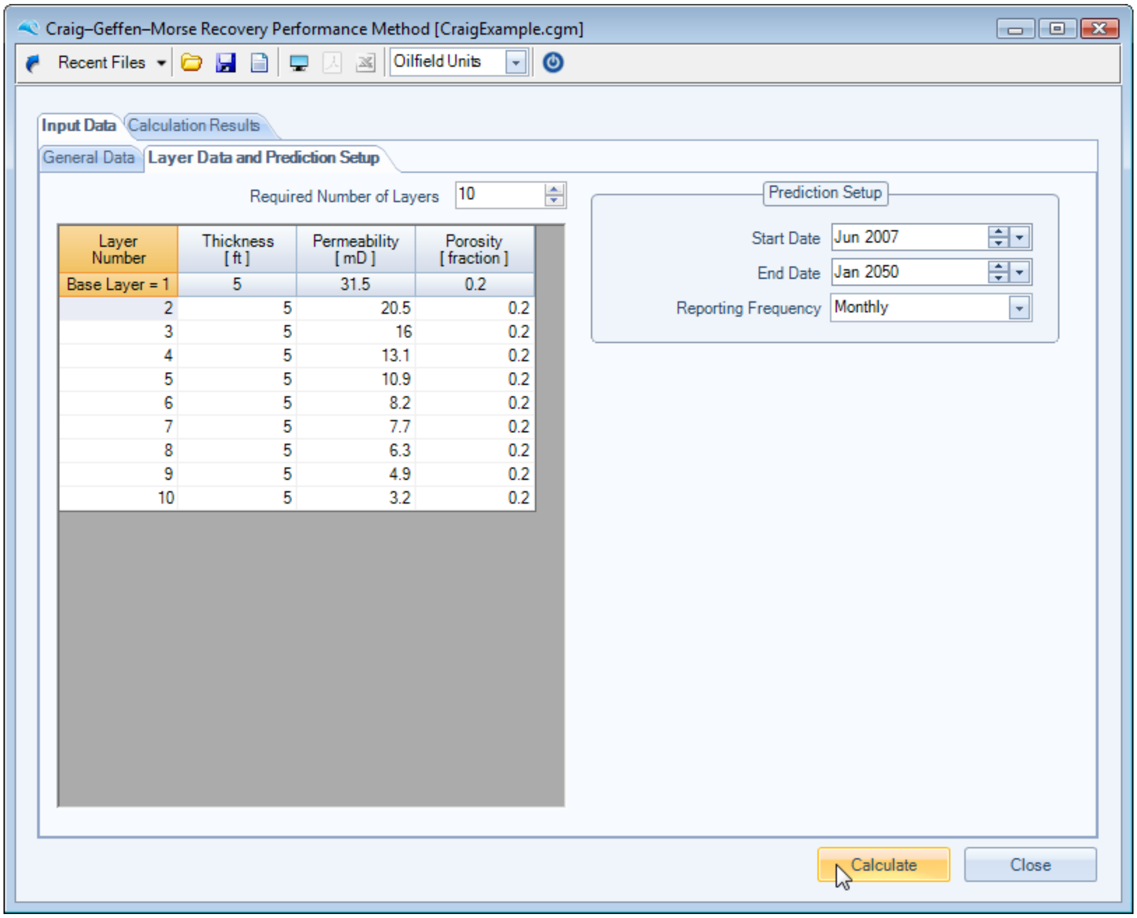
Layer Properties

Layer Number	Thickness [ft]	Permeability [mD]	Porosity [fraction]
1	5	31.5	0.2
2	5	20.5	0.2
3	5	16	0.2
4	5	13.1	0.2
5	5	10.9	0.2
6	5	8.2	0.2
7	5	7.7	0.2
8	5	6.3	0.2
9	5	4.9	0.2
10	5	3.2	0.2

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the ***calculate*** button to calculate all stages of the performance prediction.

The user can choose to enter Relative Permeability table values, as shown below, or choose to enter Corey coefficients for Oil and Water curvature, since all the other endpoint parameters are required for other calculation steps [kro, krw, Sor, Swc].

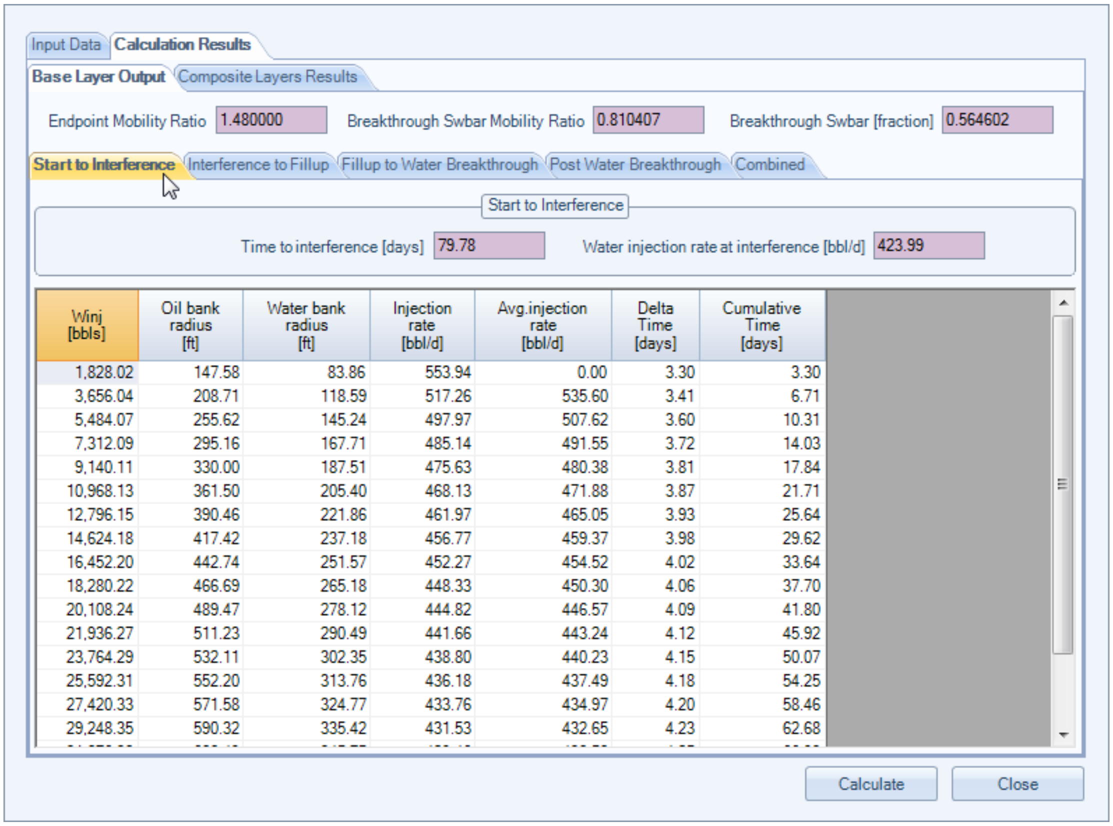

Craig–Geffen–Morse Recovery Performance Method [CraigExample.cgm]
Recent Files
Oilfield Units
Input Data
Calculation Results
General Data
Layer Data and Prediction Setup
Endpoint kro, fraction 1
Endpoint krw, fraction 0.74
Oil viscosity [cP] 1
Water viscosity [cP] 0.5
Oil FVF, Bo [rb/stb] 1.2
Water FVF, Bw [rb/stb] 1
Residual Oil Saturation, Sor [fraction] 0.3
Initial Water Saturation, Swc [fraction] 0.1
Initial Gas Saturation, Sgi [fraction] 0.15
Injector wellbore radius [ft] 1
Pressure difference injector-producer [psi] 3000
Half distance between injectors [ft] 660
Distance injector to producer [ft] 932
Pattern Area Acres 40
Base Layer Properties
Base Layer Reservoir Thickness [ft] 5
Base Layer Permeability [mD] 31.5
Base Layer Porosity [fraction] 0.2
Input Relative Permeability
Chart
Input Corey Coefficients
Input Table Values
Input Table Values
Sw [fraction] kro [fraction] krw [fraction]
0.100000 1.000000 0.000000
0.300000 0.373000 0.070000
0.400000 0.210000 0.169000
0.450000 0.148000 0.226000
0.500000 0.100000 0.300000
0.550000 0.061000 0.376000
0.600000 0.033000 0.476000
0.650000 0.012000 0.600000
0.700000 0.000000 0.740000
Calculate
Close



Stage 1 : Start to Interference

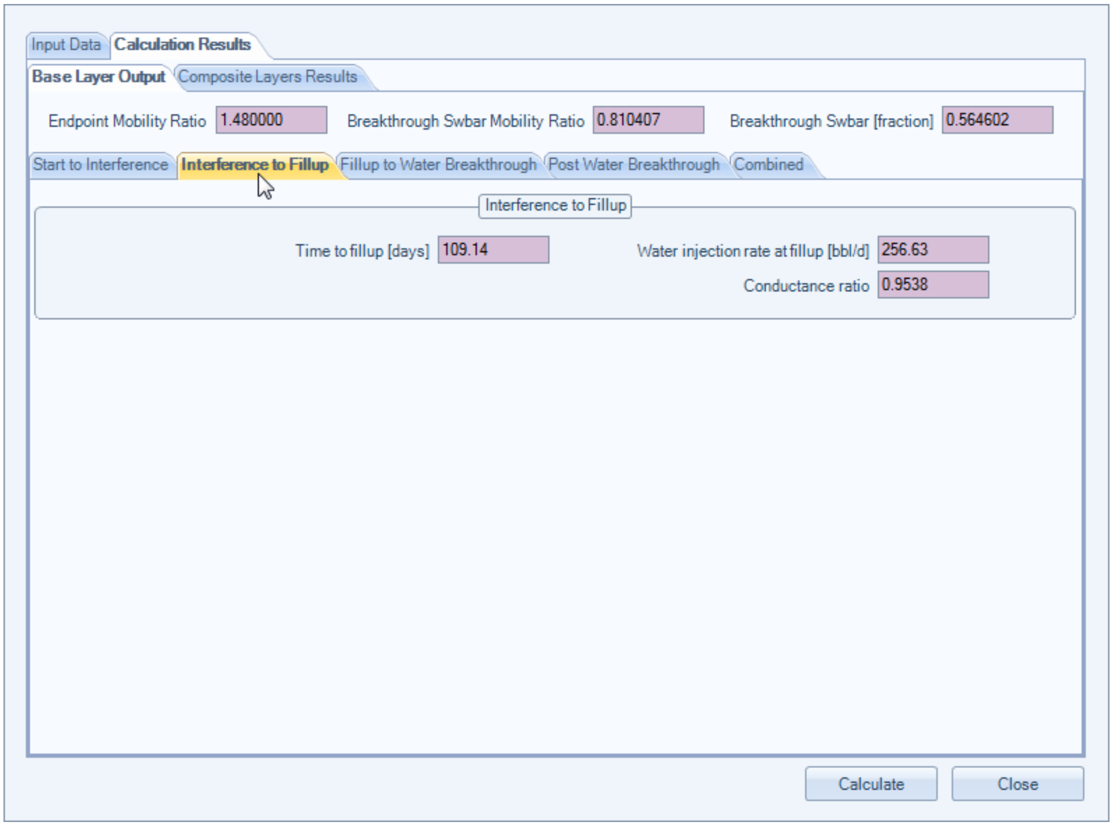
The Stage 1 - Start to Interference is calculated if the user input an initial gas saturation value > 0.

Note that all data within the tables can be output to the clipboard by pressing CTRL+C



Stage 2 : Interference to Fillup

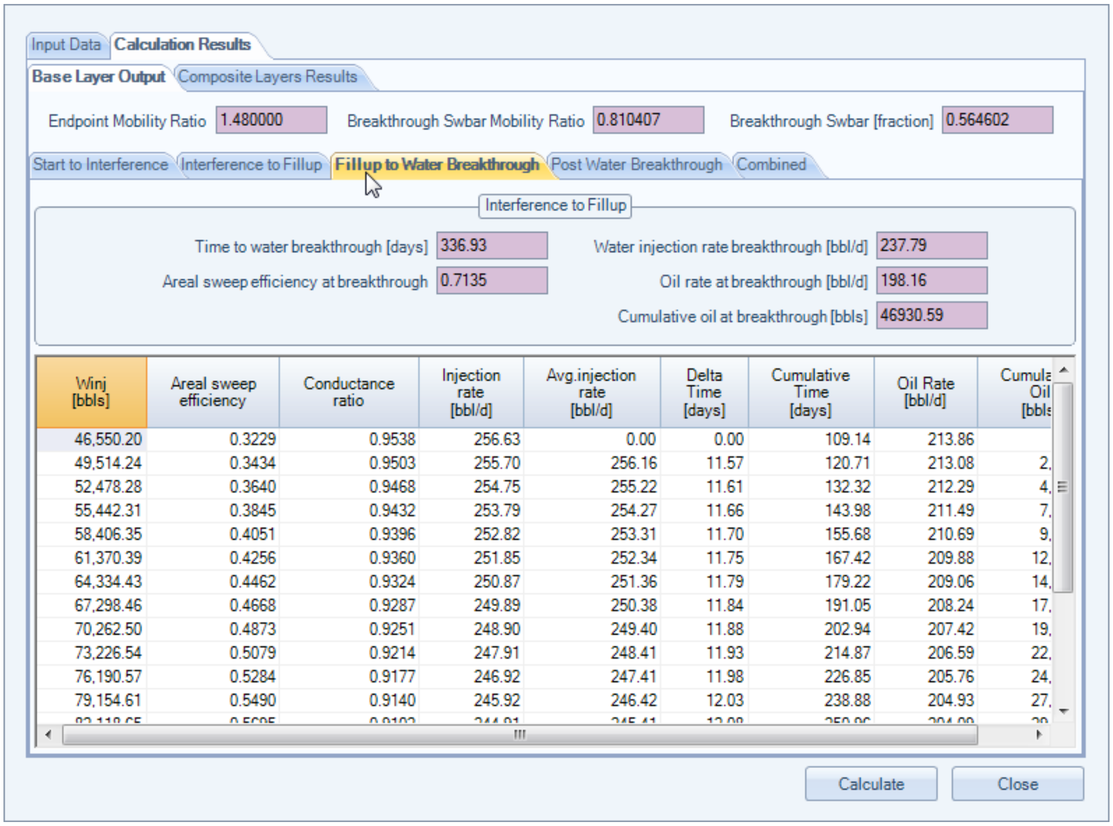
The Stage 2 - Interference to Fillup is also calculated if the user input an initial gas saturation value > 0.



Stage 3 : Fillup to Water Breakthrough

The Stage 3 - Fillup to Water Breakthrough calculation panel is shown below :

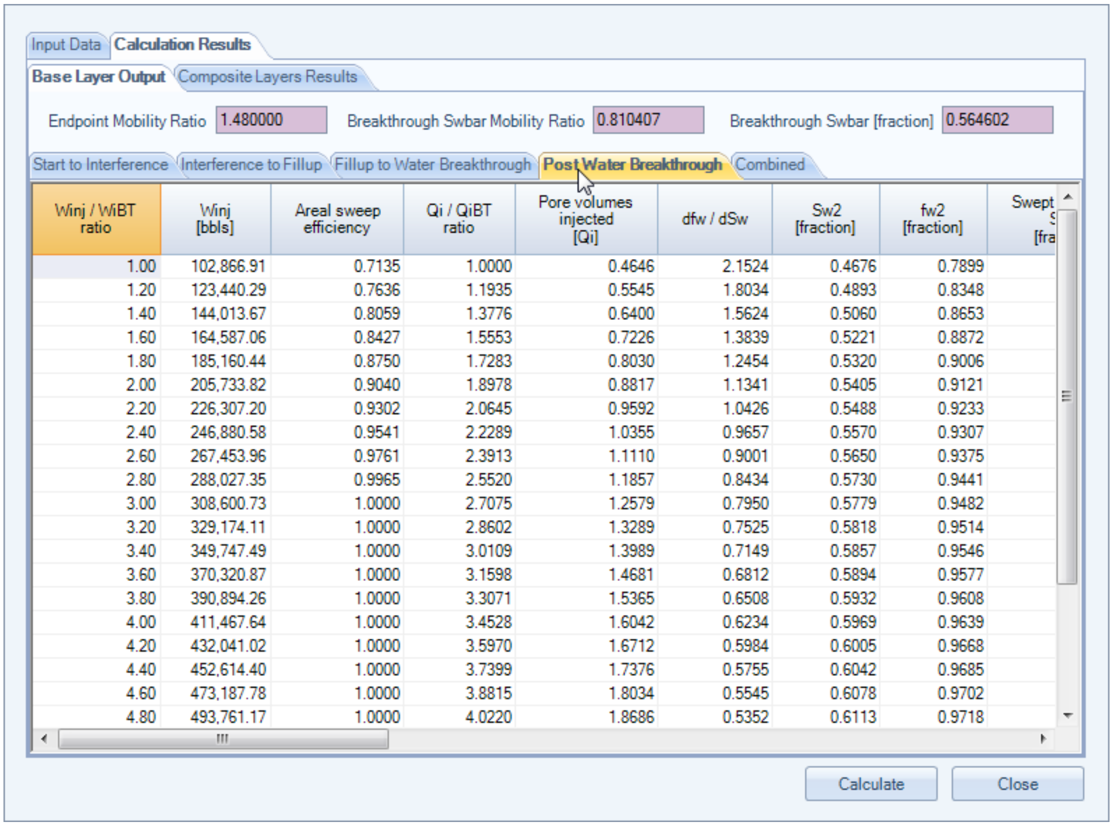
Note that all data within the tables can be output to the clipboard by pressing CTRL+C



Stage 4 : Post Water Breakthrough

The Stage 4 - Post Water Breakthrough calculation output panel is shown below :

Note that all data within the tables can be output to the clipboard by pressing CTRL+C

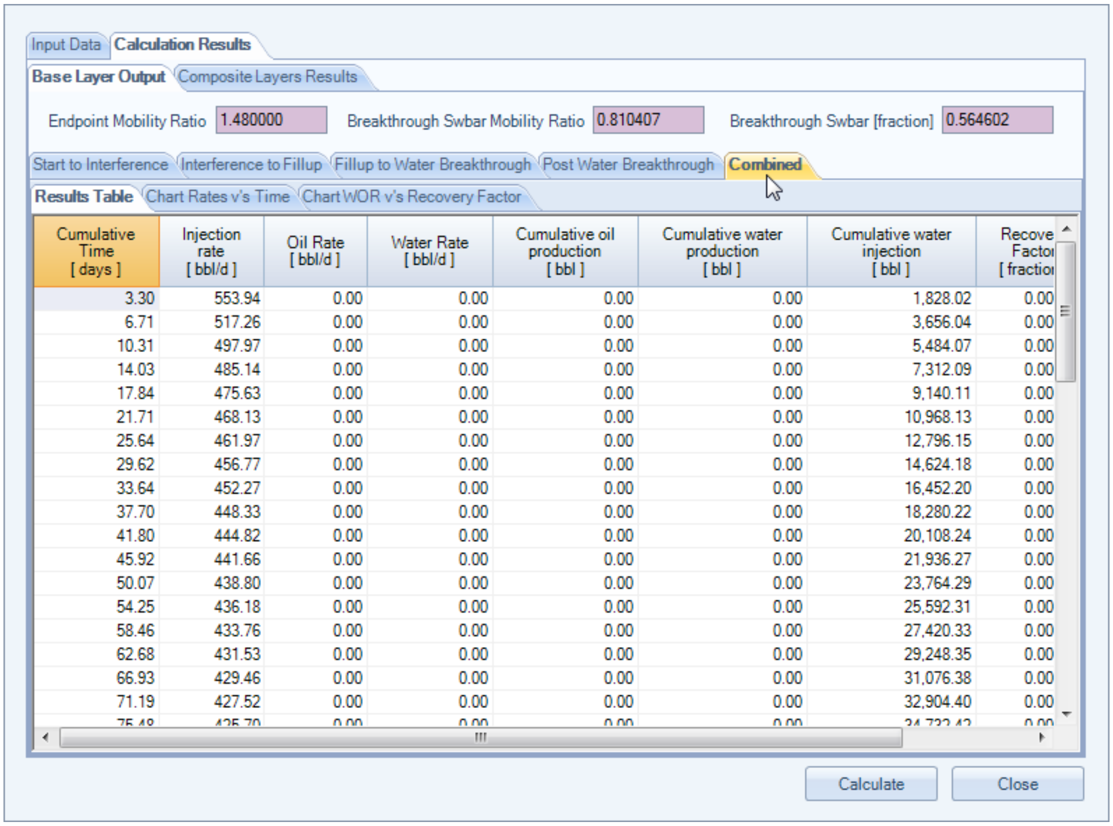


Winj / WiBT ratio	Winj [bbls]	Areal sweep efficiency	Qi / QiBT ratio	Pore volumes injected [Qi]	dfw / dSw	Sw2 [fraction]	fw2 [fraction]	Swept [fra
1.00	102,866.91	0.7135	1.0000	0.4646	2.1524	0.4676	0.7899	
1.20	123,440.29	0.7636	1.1935	0.5545	1.8034	0.4893	0.8348	
1.40	144,013.67	0.8059	1.3776	0.6400	1.5624	0.5060	0.8653	
1.60	164,587.06	0.8427	1.5553	0.7226	1.3839	0.5221	0.8872	
1.80	185,160.44	0.8750	1.7283	0.8030	1.2454	0.5320	0.9006	
2.00	205,733.82	0.9040	1.8978	0.8817	1.1341	0.5405	0.9121	
2.20	226,307.20	0.9302	2.0645	0.9592	1.0426	0.5488	0.9233	
2.40	246,880.58	0.9541	2.2289	1.0355	0.9657	0.5570	0.9307	
2.60	267,453.96	0.9761	2.3913	1.1110	0.9001	0.5650	0.9375	
2.80	288,027.35	0.9965	2.5520	1.1857	0.8434	0.5730	0.9441	
3.00	308,600.73	1.0000	2.7075	1.2579	0.7950	0.5779	0.9482	
3.20	329,174.11	1.0000	2.8602	1.3289	0.7525	0.5818	0.9514	
3.40	349,747.49	1.0000	3.0109	1.3989	0.7149	0.5857	0.9546	
3.60	370,320.87	1.0000	3.1598	1.4681	0.6812	0.5894	0.9577	
3.80	390,894.26	1.0000	3.3071	1.5365	0.6508	0.5932	0.9608	
4.00	411,467.64	1.0000	3.4528	1.6042	0.6234	0.5969	0.9639	
4.20	432,041.02	1.0000	3.5970	1.6712	0.5984	0.6005	0.9668	
4.40	452,614.40	1.0000	3.7399	1.7376	0.5755	0.6042	0.9685	
4.60	473,187.78	1.0000	3.8815	1.8034	0.5545	0.6078	0.9702	
4.80	493,761.17	1.0000	4.0220	1.8686	0.5352	0.6113	0.9718	

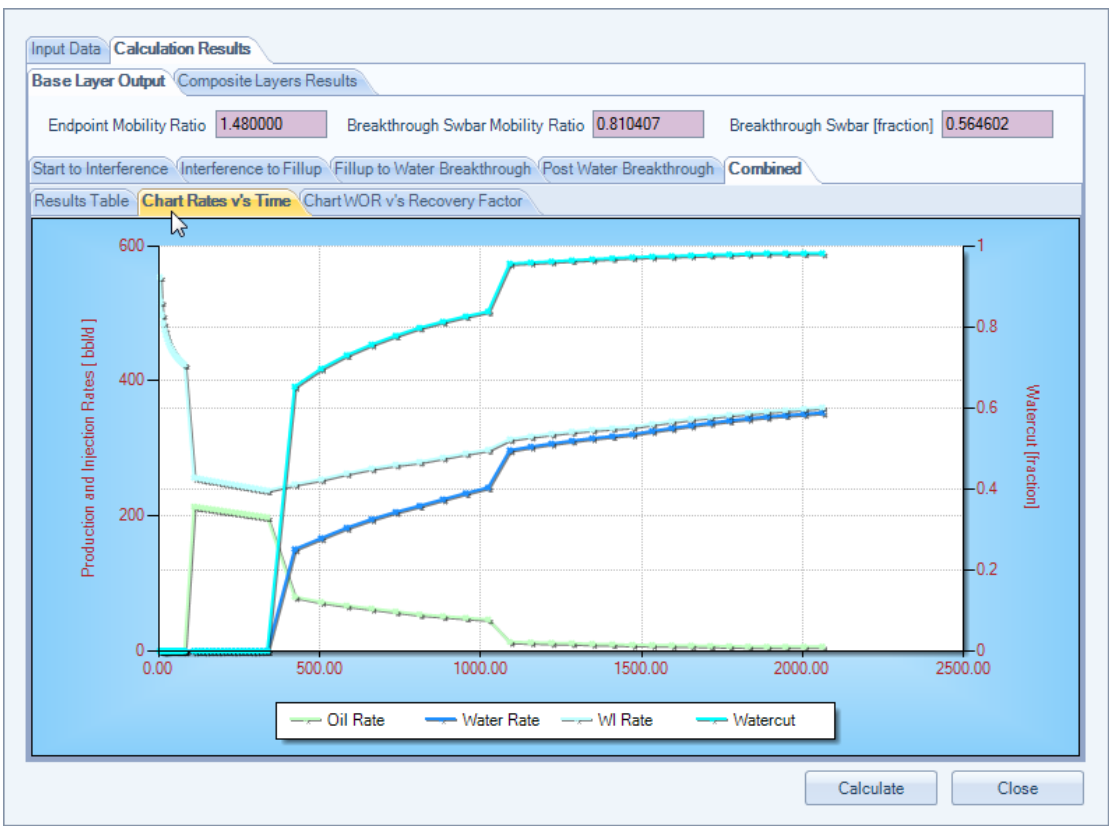
Stage 5 : Combined Base Layer Profile Prediction

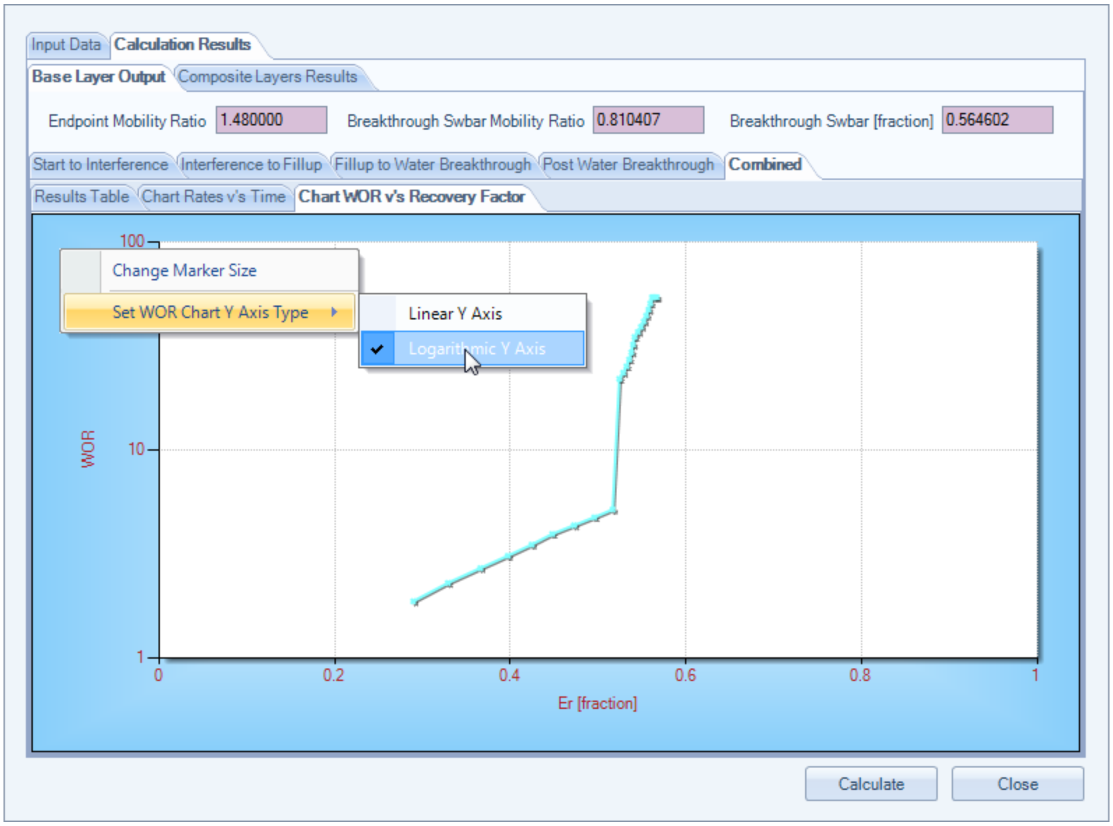
The combined base layer performance output panel and charts are shown below :

Note that all data within the tables can be output to the clipboard by pressing CTRL+C



Cumulative Time [days]	Injection rate [bbl/d]	Oil Rate [bbl/d]	Water Rate [bbl/d]	Cumulative oil production [bbl]	Cumulative water production [bbl]	Cumulative water injection [bbl]	Recove Factor [fractio
3.30	553.94	0.00	0.00	0.00	0.00	1,828.02	0.00
6.71	517.26	0.00	0.00	0.00	0.00	3,656.04	0.00
10.31	497.97	0.00	0.00	0.00	0.00	5,484.07	0.00
14.03	485.14	0.00	0.00	0.00	0.00	7,312.09	0.00
17.84	475.63	0.00	0.00	0.00	0.00	9,140.11	0.00
21.71	468.13	0.00	0.00	0.00	0.00	10,968.13	0.00
25.64	461.97	0.00	0.00	0.00	0.00	12,796.15	0.00
29.62	456.77	0.00	0.00	0.00	0.00	14,624.18	0.00
33.64	452.27	0.00	0.00	0.00	0.00	16,452.20	0.00
37.70	448.33	0.00	0.00	0.00	0.00	18,280.22	0.00
41.80	444.82	0.00	0.00	0.00	0.00	20,108.24	0.00
45.92	441.66	0.00	0.00	0.00	0.00	21,936.27	0.00
50.07	438.80	0.00	0.00	0.00	0.00	23,764.29	0.00
54.25	436.18	0.00	0.00	0.00	0.00	25,592.31	0.00
58.46	433.76	0.00	0.00	0.00	0.00	27,420.33	0.00
62.68	431.53	0.00	0.00	0.00	0.00	29,248.35	0.00
66.93	429.46	0.00	0.00	0.00	0.00	31,076.38	0.00
71.19	427.52	0.00	0.00	0.00	0.00	32,904.40	0.00



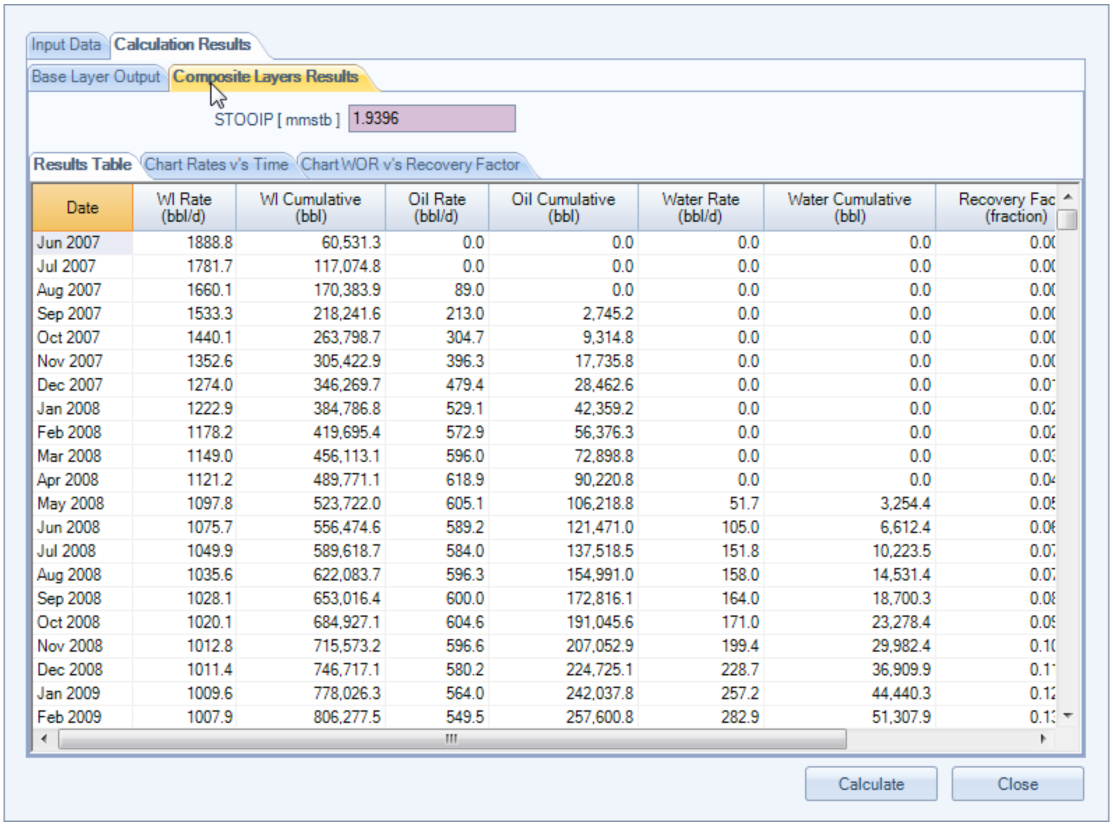


To switch between a Linear Y Axis and a Logarithmic Y Axis on the above WOR Vs Er plot, select the chart's context menu by a single right mouse click within the chart area.

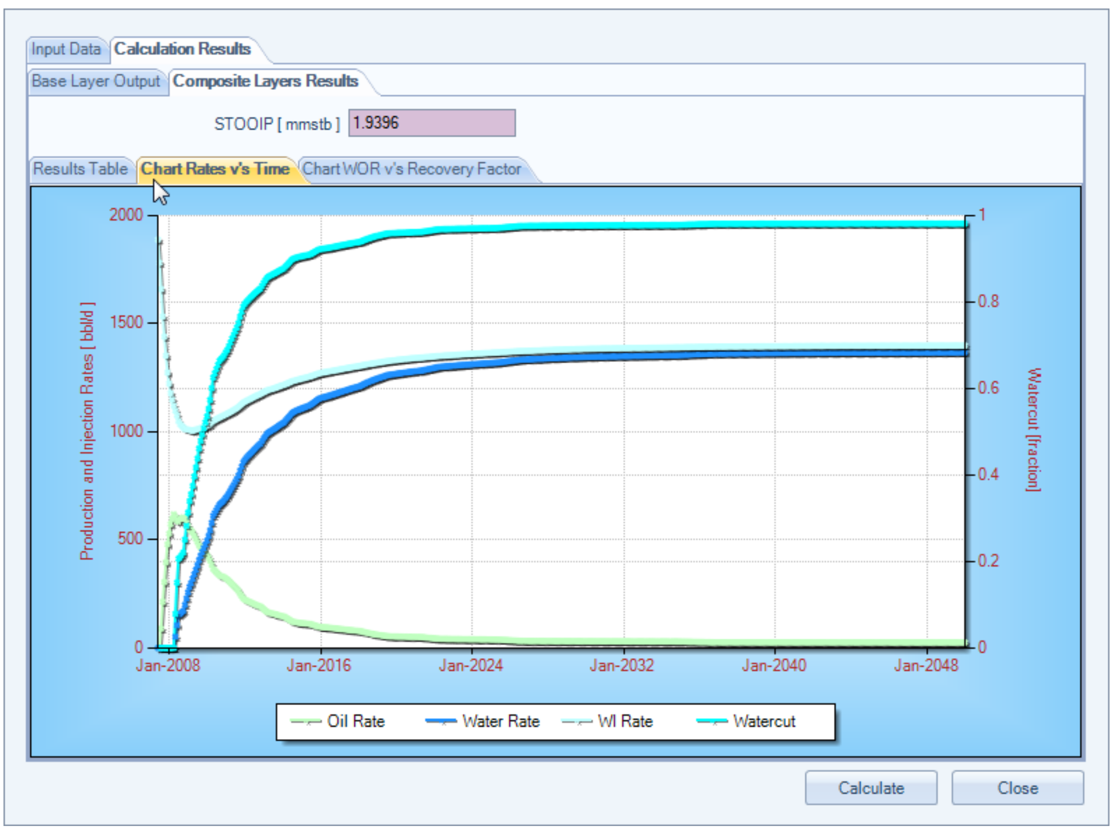
Stage 6 : Combined All Layers Profile Prediction

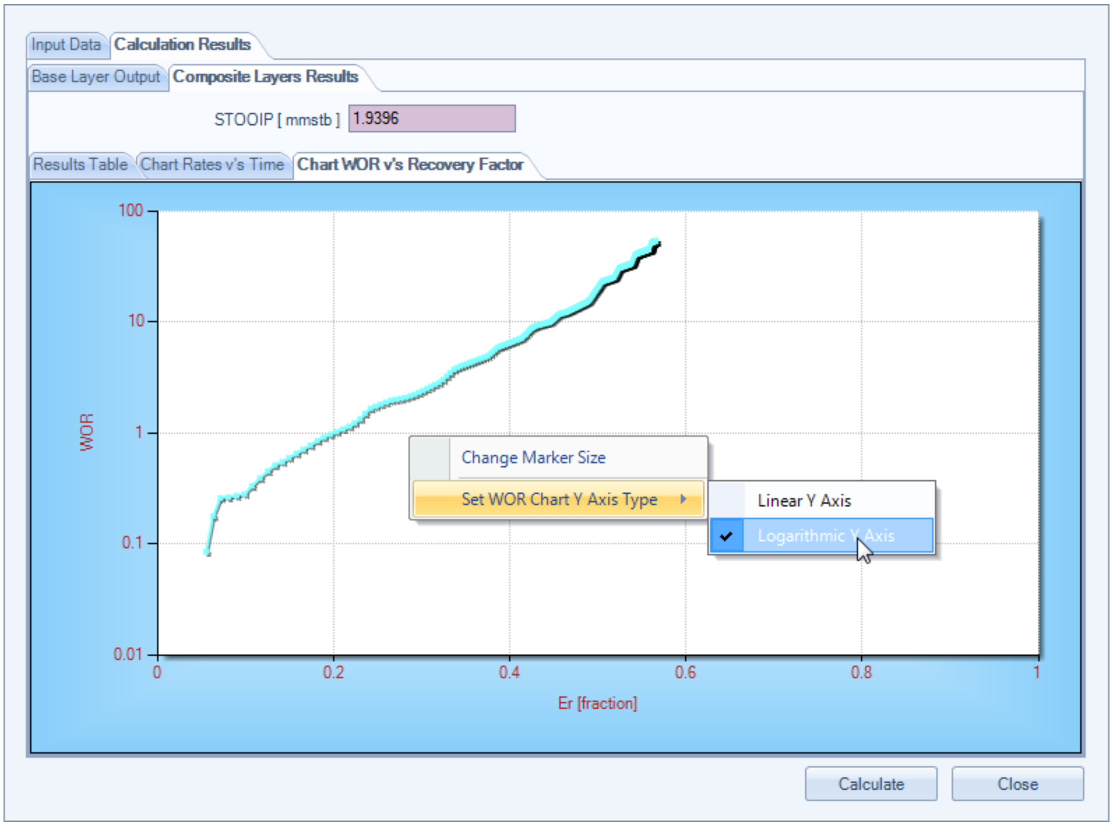
The combined all layers performance output panel and charts are shown below.

Note that all data within the tables can be output to the clipboard by pressing CTRL+C



Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Water Rate (bbl/d)	Water Cumulative (bbl)	Recovery Fac (fraction)
Jun 2007	1888.8	60,531.3	0.0	0.0	0.0	0.0	0.00
Jul 2007	1781.7	117,074.8	0.0	0.0	0.0	0.0	0.00
Aug 2007	1660.1	170,383.9	89.0	0.0	0.0	0.0	0.00
Sep 2007	1533.3	218,241.6	213.0	2,745.2	0.0	0.0	0.00
Oct 2007	1440.1	263,798.7	304.7	9,314.8	0.0	0.0	0.00
Nov 2007	1352.6	305,422.9	396.3	17,735.8	0.0	0.0	0.00
Dec 2007	1274.0	346,269.7	479.4	28,462.6	0.0	0.0	0.01
Jan 2008	1222.9	384,786.8	529.1	42,359.2	0.0	0.0	0.02
Feb 2008	1178.2	419,695.4	572.9	56,376.3	0.0	0.0	0.02
Mar 2008	1149.0	456,113.1	596.0	72,898.8	0.0	0.0	0.03
Apr 2008	1121.2	489,771.1	618.9	90,220.8	0.0	0.0	0.04
May 2008	1097.8	523,722.0	605.1	106,218.8	51.7	3,254.4	0.05
Jun 2008	1075.7	556,474.6	589.2	121,471.0	105.0	6,612.4	0.06
Jul 2008	1049.9	589,618.7	584.0	137,518.5	151.8	10,223.5	0.07
Aug 2008	1035.6	622,083.7	596.3	154,991.0	158.0	14,531.4	0.07
Sep 2008	1028.1	653,016.4	600.0	172,816.1	164.0	18,700.3	0.08
Oct 2008	1020.1	684,927.1	604.6	191,045.6	171.0	23,278.4	0.09
Nov 2008	1012.8	715,573.2	596.6	207,052.9	199.4	29,982.4	0.10
Dec 2008	1011.4	746,717.1	580.2	224,725.1	228.7	36,909.9	0.11
Jan 2009	1009.6	778,026.3	564.0	242,037.8	257.2	44,440.3	0.12
Feb 2009	1007.9	806,277.5	549.5	257,600.8	282.9	51,307.9	0.13





The user can choose to display the Y axis of the WOR versus recovery factor as a logarithmic scale, in line with common industry practice. To switch between a Linear Y Axis and a Logarithmic Y Axis on the above plot, select the chart's context menu by a single right mouse click within the chart area.

References:

Craig, Jr., F., *"The Reservoir Engineering Aspects of Waterflooding"*, Society of Petroleum Engineers, 1971

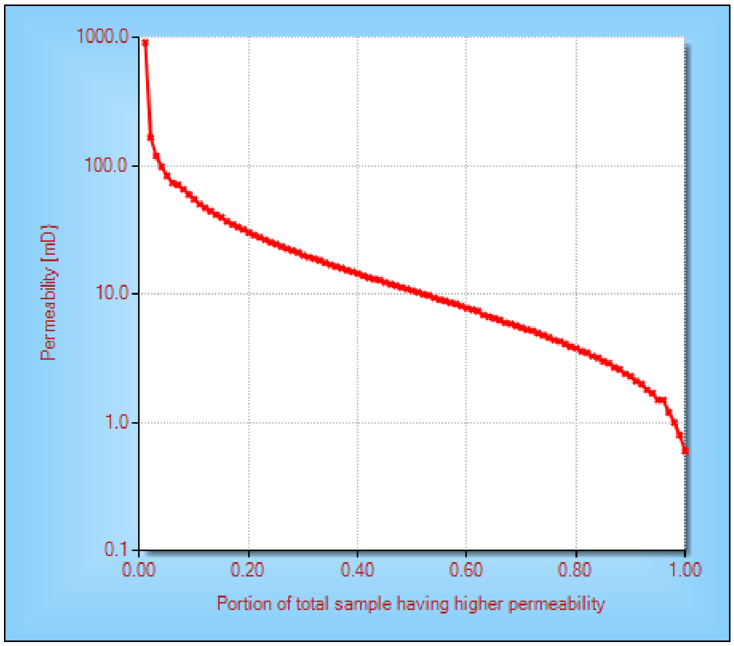
Part IV

4 Dykstra-Parsons

4.1 Heterogeneity Coefficients

Dykstra and Parsons introduced the concept of the permeability variation V, which is designed to describe the degree of heterogeneity within the reservoir. Values for this coefficient range between zero for a completely homogeneous system and one for a completely heterogeneous system.

To obtain the value of permeability variation V, the permeability dataset is sorted from minimum to maximum and displayed on a chart of log probability scale, as shown below.



The equation for permeability variation V is included below.

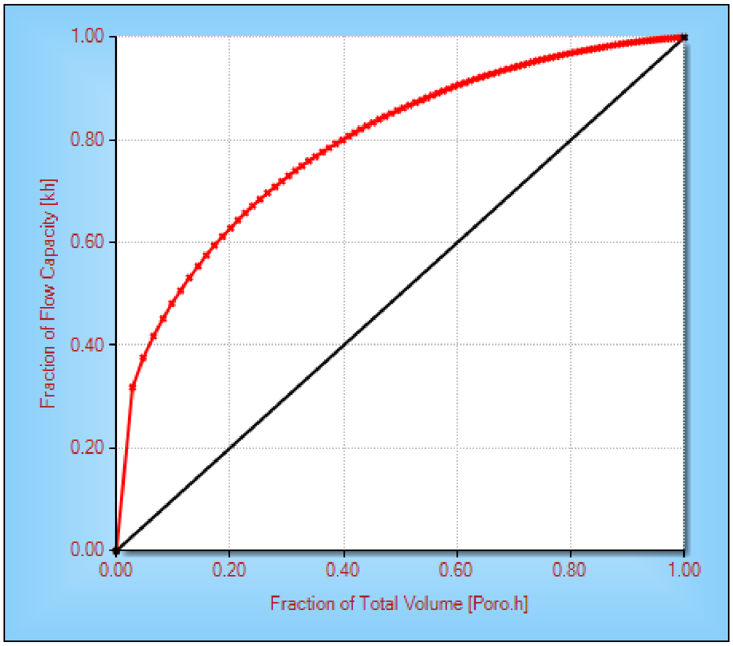
$$V = \frac{stdev(Log(k))}{avg(Log(k))} = \frac{Log(k)_{P50} - Log(k)_{P84.1}}{Log(k)_{P50}}$$

Both of the above equations have been implemented into this routine. The significance of the Log(k) at a probability value of 84.1% is that it is the equivalent of one standard deviation away from the 50% probability value assuming a log normal distribution (which permeability distributions often displays this characteristic).

In 1950, Schmalz and Rahme proposed a single term for characterizing the permeability distribution within a pay section. Referring to the chart below, they defined the Lorenz coefficient of heterogeneity as the (area between the green curve and the red curve) / (area between the red curve and the X axis).

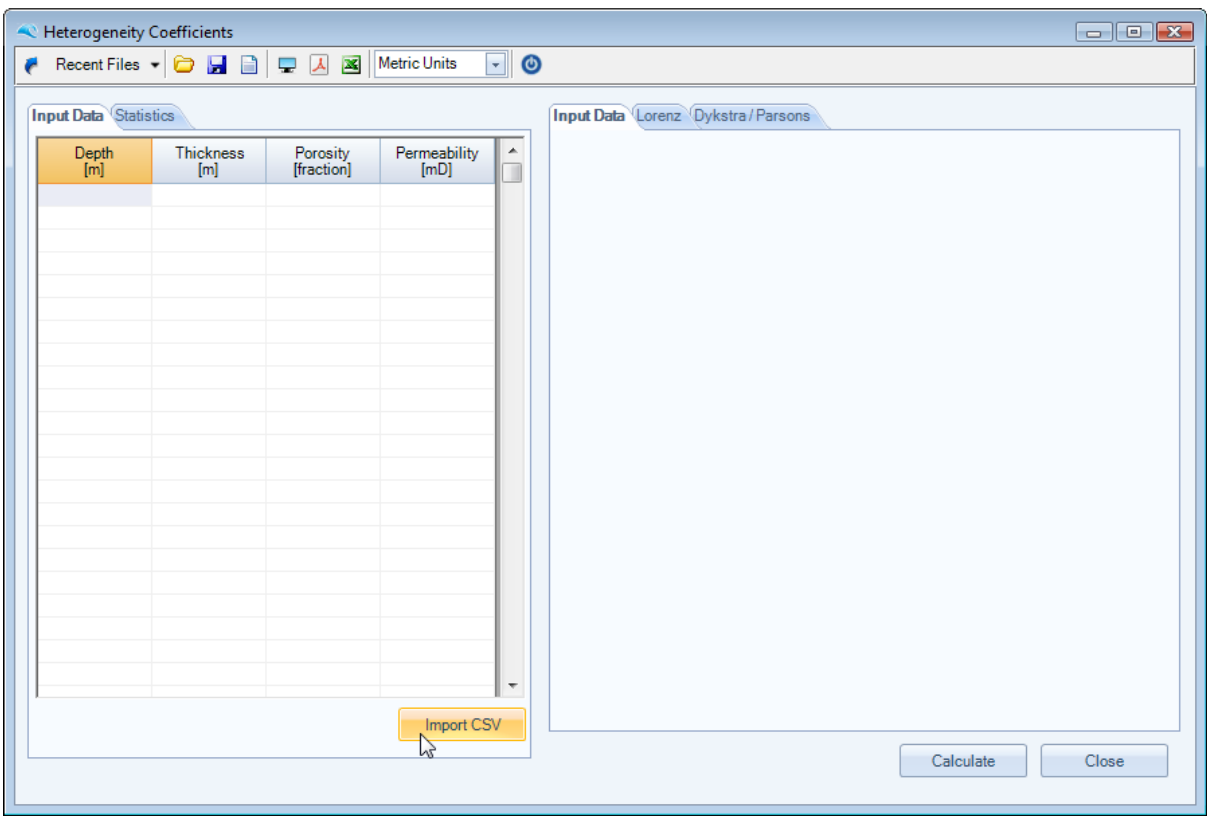
The value of the Lorenz coefficient ranges from 0 to 1, a uniform permeability reservoir having a Lorenz coefficient of zero.

This calculation and display has also been included within this routine.



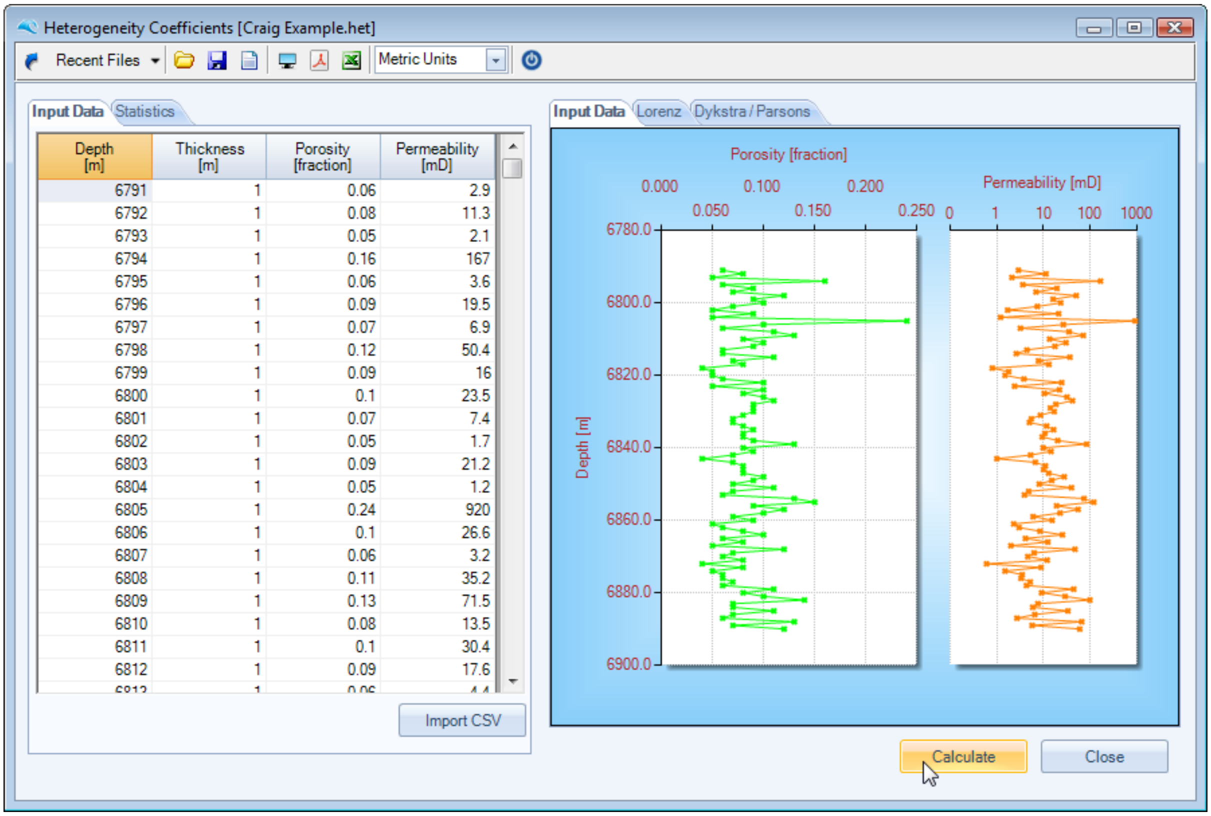
The following example is taken from data presented in Craig's SPE Monograph *"The Reservoir Engineering Aspects of Waterflooding"*, to better explain the various aspects of this routine.

Once the routine is launched the following input screen is displayed.

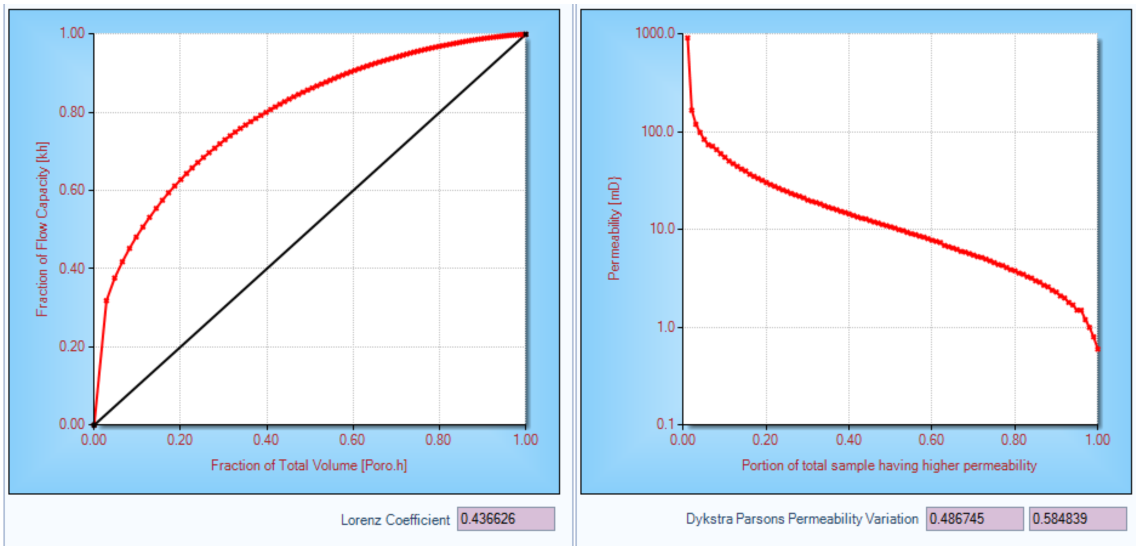


The user can input data either by using the Import CSV button to load a comma delimited ASCII file, or simply copy and paste or drag and drop data from an external application, such as Microsoft Excel.

Once the data has been input, the user should press the calculate button to display the charts of porosity and permeability versus depth, together with the Lorenz and Dykstra-Parsons charts and calculated coefficients. At this point the following should be displayed.

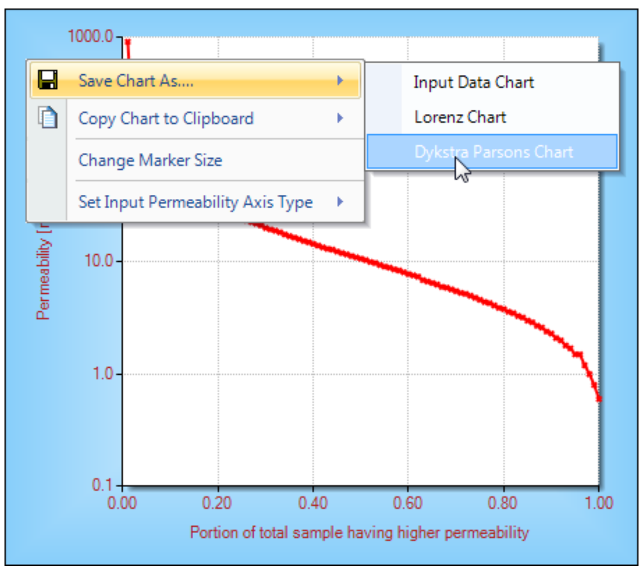


Selecting the Lorenz TAB display the Lorenz chart and calculated coefficient. Likewise, selecting the Dykstra-Parsons TAB display the Dykstra-Parsons chart and calculated coefficients. Both examples are provided below. The first coefficient in the Dykstra-Parsons TAB is calculated from the Average and Standard Deviation, whereas the second coefficient is calculated from interpolated values of P50 and P84.1.

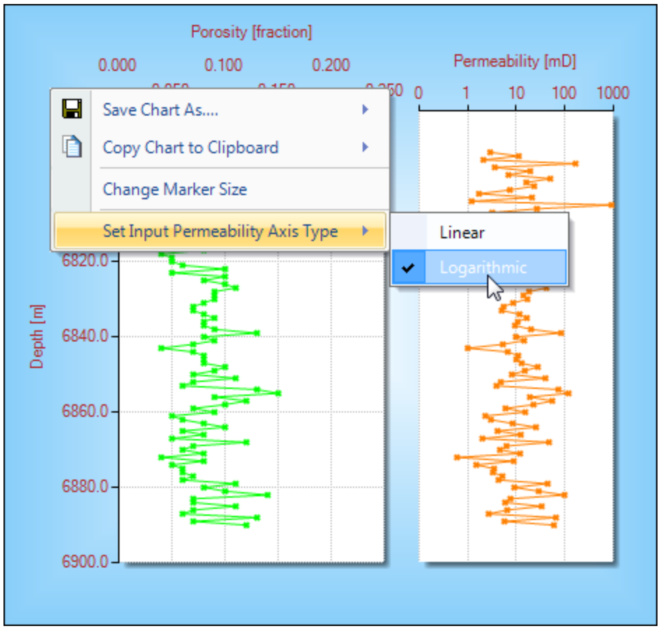


Exporting Charts to Clipboard or File

The user can quickly copy and paste the chart to the Windows clipboard or save the chart as a graphic image file by selecting the context menu (right-muse click) while the mouse is within the chart area. The following should be displayed.



Also the user can also choose to display the permeability versus depth chart as a logarithmic scale for permeability, is required. This is also shown below.



References:

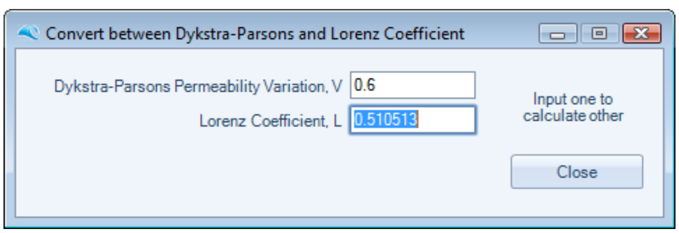
Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States*,* 2nd ed. American Petroleum Institute, 1950

Schmalz, J. P. and Rahme, H. D., "*The Variation of Waterflood Performance With Variation in Permeability Profile*", Prod. Monthly, 1950.

Craig, Jr., F., *"The Reservoir Engineering Aspects of Waterflooding"*, Society of Petroleum Engineers, 1971

4.2 Dykstra-Parsons and Lorenz Coefficient

A simple routine has been included to convert between Dykstra-Parsons and Lorenz coefficients. The input screen is included for completeness below.



Simply enter a number into a blank cell, then TAB out of the cell or mouse click the other blank cell, to calculate the required coefficient.

References:

Warren, J. E. and Price, H. S., “Flow in Heterogeneous Porous Media,” *SPE Paper 1579-G,* 1961

4.3 Vertical Sweep

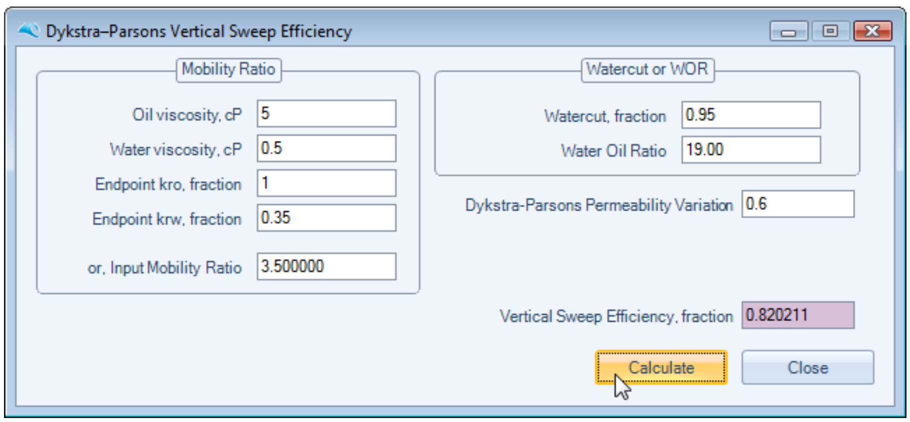
Dykstra and Parsons correlated vertical sweep efficiency with the following parameters:

- Permeability variation, V
- Mobility ratio, M
- Water–oil ratio

The authors presented their correlation in a graphical form for water–oil ratios of 0.1, 0.2, 0.5, 1, 2, 5, 10, 25, 50, and 100 bbl/bbl.

Using a regression analysis model, de Souza and Brigham grouped the vertical sweep efficiency curves for 0 = M = 10 and 0.3 = V
= 0.8 into one curve and developed a regression equation that has been implemented into this routine.

Simply enter the required input data, then press the *Calculate* button, as shown below.



References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States*,* 2nd ed. American Petroleum Institute, 1950

de Souza, A., Brigham, W., "*A Study on Dykstra–Parsons Curves*", Stanford University Petroleum Research Institute, 1981

4.4 Recovery Performance

When predicting reservoir performance to include the effects of reservoir vertical heterogeneity, the reservoir is represented by a series of layers with no vertical communication (no cross-flow between layers).

Two Dykstra–Parsons methods are discussed in more detail in this section. Both of these methods use the Dykstra–Parsons heterogeneity index to describe the vertical permeability variation, as opposed to describing each layer's value of thickness, permeability, and porosity, as presented in the Dake-Welge and Craig-Geffen-Morse methods implemented in previous sections.

References:

Ahmed, T., "*Reservoir Engineering Handbook*", Elsevier, 2006

4.4.1 Simplified Method

Dykstra and Parsons presented a correlation for predicting waterflood oil recovery that uses the mobility ratio, permeability variation, and producing water–oil ratio as correlating parameters.

Johnson developed a simplified graphical approach for the Dykstra and Parsons method that is based on predicting the overall oil recovery at water–oil ratios (WOR) of 1, 5, 25, and 100 bbl/bbl.

The technique of calculating the simplified Dykstra and Parsons method is presented below :

1. Calculate the permeability variation and mobility ratio.

2. The overall oil recovery factor is calculated from four WOR values of 1, 5, 25, 100 bbl/bbl. The original curves of Johnson have been digitised and input into this routine to permit interpolation between permeability variation and mobility ratio. The oil recovery factor at water breakthrough is calculated by extrapolating back to a WOR of zero.

3. Calculate the cumulative oil production at each of the four WOR values, and the cumulative oil production at water breakthrough for a WOR = 0, from the following :

$$N_p = N_S.R$$

4. For a constant injection rate, adding the fill-up volume Wif to the cumulative oil produced at breakthrough and dividing by the injection rate will estimate the time to breakthrough.

5. The equation to link water injection to oil and water production and fillup volume is presented below. This equation is used together with the relationship of WOR Vs overall oil recovery factor to derive the oil and water production rates versus time.

$$W_{inj} = N_p B_o + W_p B_w + W_{if}$$

References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

Johnson, C., "*Prediction of Oil Recovery by Waterflood - A Simplified Graphical Treatment of the Dykstra-Parsons Method*" AIME, 1956

Ahmed, T., "*Reservoir Engineering Handbook*", Elsevier, 2006

4.4.2 Extended Method

This technique of calculating the extended Dykstra and Parsons method is presented below :

1. From the relative permeability data and oil and water viscosities, calculate the fractional flow relationship from the following

$$f_{w2} = \frac{1}{1 + \frac{\mu_w}{\mu_o} . \frac{k_{ro}}{k_{rw}}}$$

2. Calculate the slope of dfw/dSw and determine the average water saturation at breakthrough.

3. Calculate the displacement efficiency at breakthrough, from :

$$E_D = \frac{\overline{S}_w - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}}$$

4. Calculate the areal sweep efficiency at breakthrough, from :

$$E_A = \frac{1}{1 + A}$$

where.

$$A = \left(a_1.\ln\left(M + a_2\right) + a_3\right).f_w + a_4.\ln\left(M + a_5\right) + a_6$$

Where coefficients a_1 to a_6 in the above equation depend on the waterdrive mechanism; ie., Five Spot, Direct Line Drive or Staggered Line Drive.

5. Calculate the vertical sweep efficiency at assumed reservoir water–oil ratios (WOR) of 1, 2, 5, 10, 15, 20, 25, 50, and 100 bbl/bbl, using the technique of de Souza and Brigham. The vertical sweep efficiency at water breakthrough is calculated by extrapolating back to a WOR of zero.

6. Calculate the fractional flow values, and surface WOR from the above assumed reservoir WOR, from the following :

$$f_{w2} = \frac{WOR_s}{WOR_r - 1} \qquad WOR_s = WOR_r\left(\frac{B_o}{B_w}\right)$$

7. Calculate cumulative water injected at breakthrough using the following equation :

$$W_{iBT} = PV.\left(\overline{S}_{wBT} - S_{wi}\right)E_{ABT}.E_{VBT}$$

8. Calculate cumulative oil produced at breakthrough, from the following :

$$N_{pBT} = \frac{W_{iBT} - W_{if}.E_{VBT}}{B_o}$$

9. Calculate the time to breakthrough, from the following :

$$t_{BT} = \frac{W_{iBT}}{q_{wi}}$$

10. Interpolate values of Sw, and calculate values of Swbar, from calculated values of fractional flow fw2, calculated previously in step 5 above.

$$\overline{S}_{w2} = S_{w2} + \frac{1 - f_{w2}}{\left(\frac{df_w}{dS_w}\right)_{S_{w2}}}$$

11. Calculate the areal sweep efficiency for each value of fw2, calculated previously in step 5 above, using equations listed in step 4 above.

12. Calculate the displacement efficiency, for each value of Swbar calculated in step 10 above, using equations listed in step 3 above.

13. Calculate cumulative oil production for each assumed WOR from the following :

$$N_p = N_S.E_D.E_A.E_V - \frac{PV.S_{gi}.(1 - E_A.E_V)}{B_o}$$

14. The equation to link water injection to oil and water production and fillup volume is presented below. This equation is used together with the relationship of WOR Vs overall oil recovery factor to derive the oil and water production rates versus time.

$$W_{inj} = N_{pWOR}.B_o + W_{pWOR}.B_w + PV.S_{gi}.E_{vWOR}$$

References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

Buckley, S., and Leverett, M., “*Mechanism of Fluid Displacement in Sands*” AIME, 1942

Felsenthal, M., Cobb, T., and Heur, G, “*A Comparison of Waterflooding Evaluation Methods*” SPE Paper 332, 1962.

de Souza, A., Brigham, W., "*A Study on Dykstra–Parsons Curves*", Stanford University Petroleum Research Institute, 1981

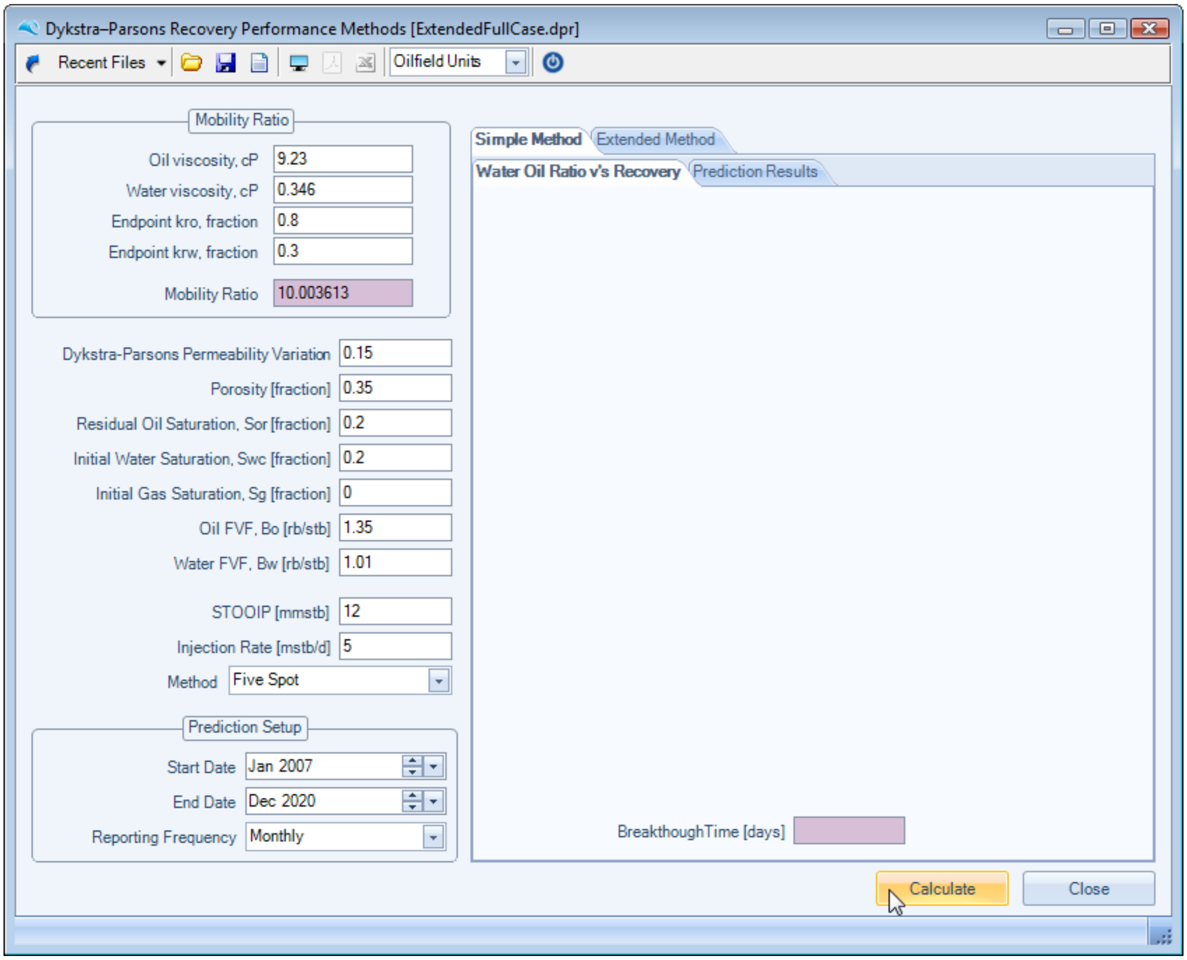
Ahmed, T., “*Reservoir Engineering Handbook*”, Elsevier, 2006

4.4.3 Example

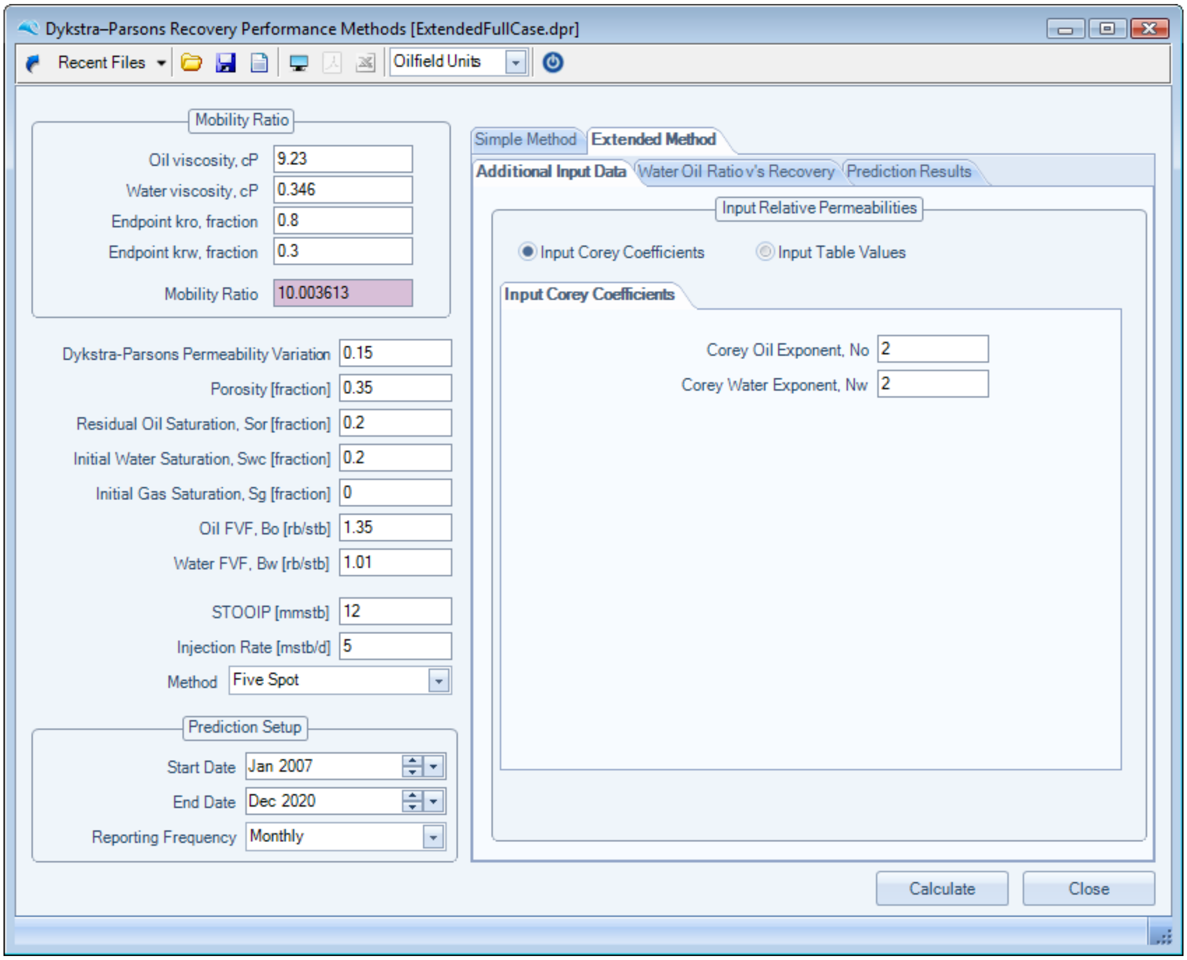
In Chapter 14 Principles of Waterflooding of Ahmed's “*Reservoir Engineering Handbook*”, he provides the following example.

General Input Data	
Oil viscosity, cP	2
Water viscosity, cP	0.5
Endpoint kro, fraction	0.4
Endpoint krw, fraction	0.3
Mobility Ratio	3
Dykstra-Parsons Permeability Variation	0.8
Porosity [fraction]	0.15
Residual Oil Saturation, Sor [fraction]	0.35
Initial Water Saturation, Swc [fraction]	0.25
Initial Gas Saturation, Sg [fraction]	0
Corey Oil Exponent	2
Corey Water Exponent	2
Oil FVF, Bo [rb/stb]	1.3
Water FVF, Bw [rb/stb]	1.05
STOOIP [mmstb]	0.716123
Injection Rate [mstb/d]	0.8
Method	Five Spot

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the ***calculate*** button to calculate all stages of the performance prediction.

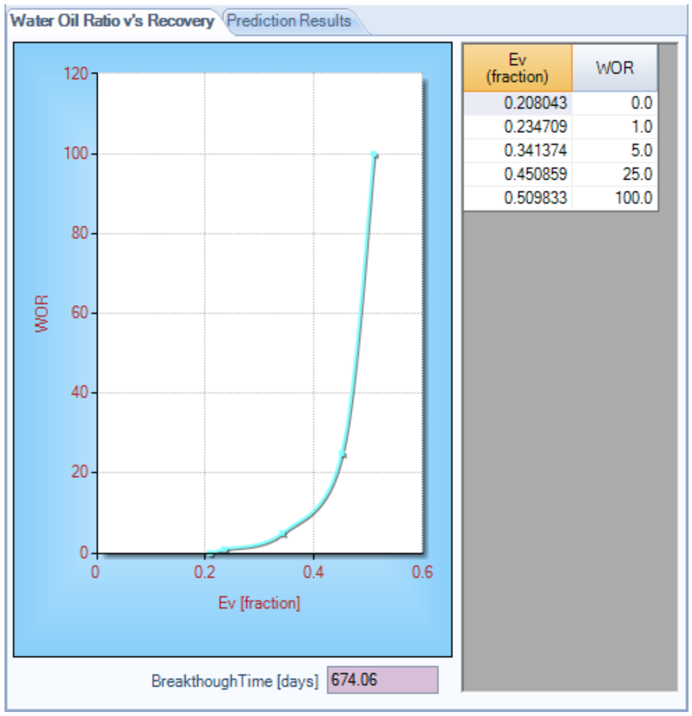


With regards to inputting relative permeability data, the user can choose between using Corey Exponents for Oil and Water curvature or inputting the table values directly. The example below assumes Corey Exponents are input.



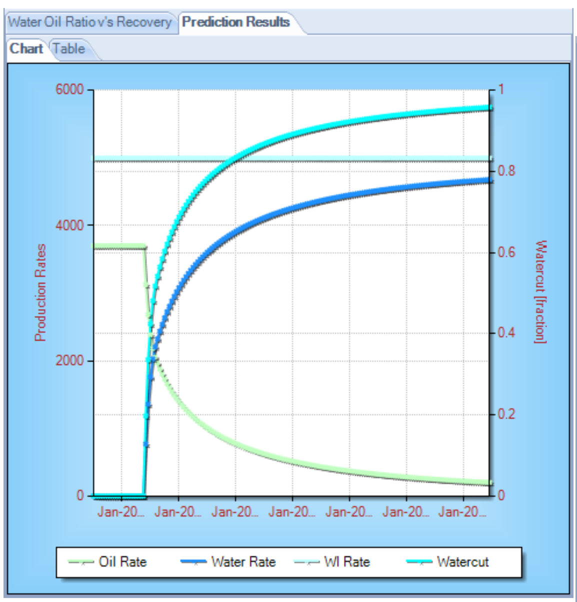
Simple Method Results

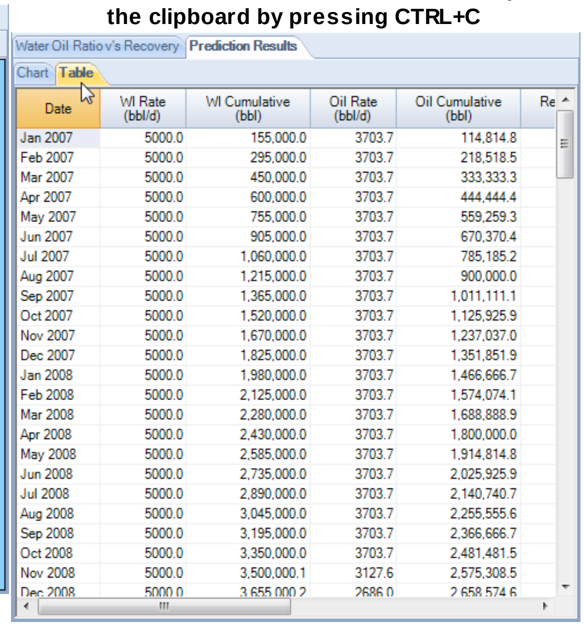
The simple method results are in the form of a WOR Vs oil recovery factory chart and table, together with a oil and water production profile and table.



Ev (fraction)	WOR
0.208043	0.0
0.234709	1.0
0.341374	5.0
0.450859	25.0
0.509833	100.0

Note that all data within the tables can be output to the clipboard by pressing CTRL+C

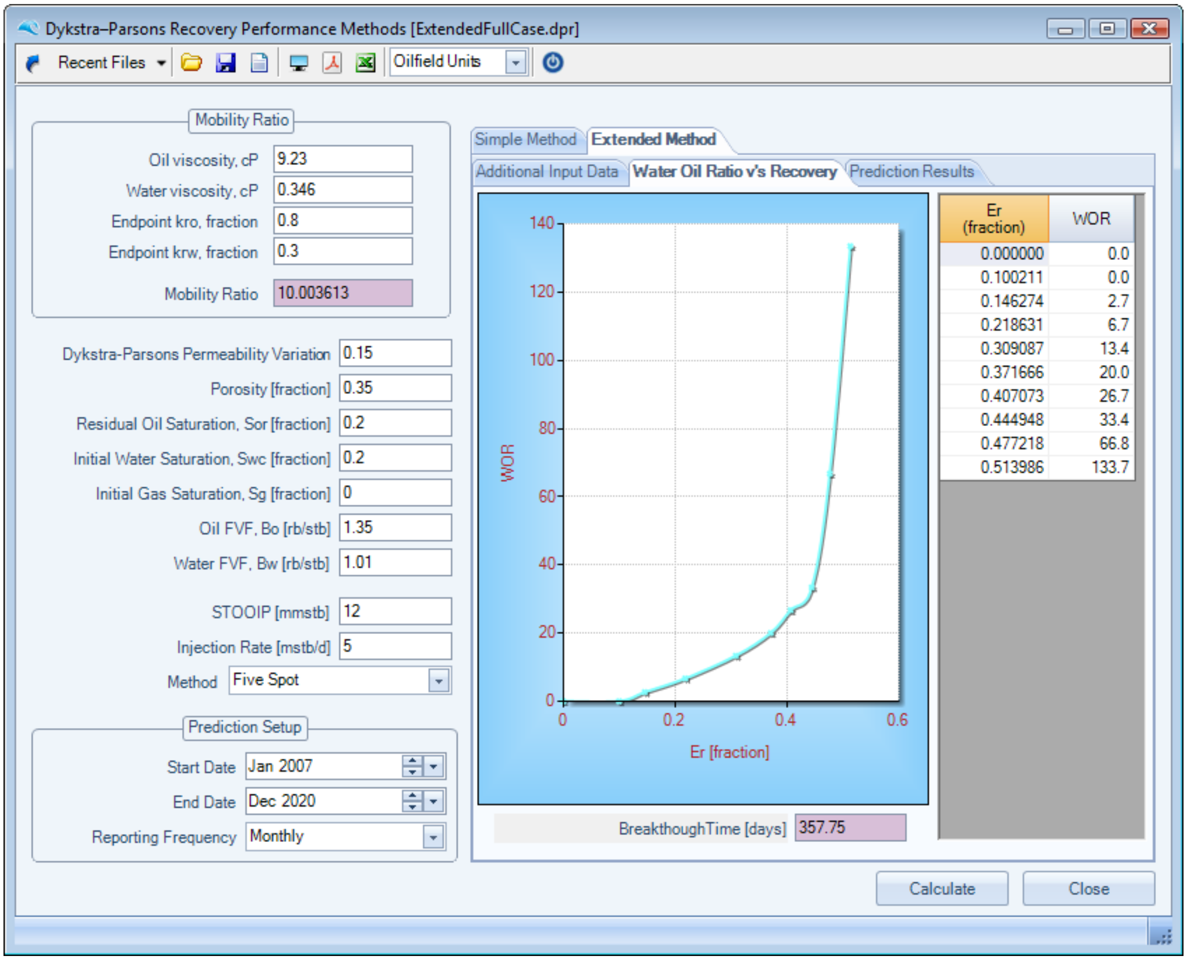




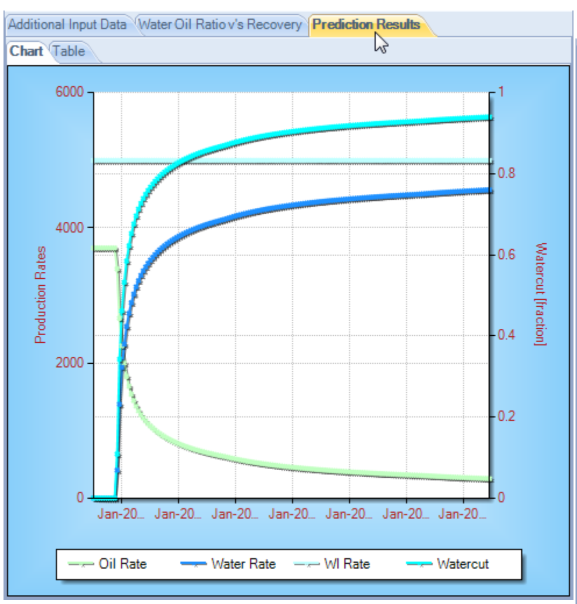
Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Re
Jan 2007	5000.0	155,000.0	3703.7	114,814.8	
Feb 2007	5000.0	295,000.0	3703.7	218,518.5	
Mar 2007	5000.0	450,000.0	3703.7	333,333.3	
Apr 2007	5000.0	600,000.0	3703.7	444,444.4	
May 2007	5000.0	755,000.0	3703.7	559,259.3	
Jun 2007	5000.0	905,000.0	3703.7	670,370.4	
Jul 2007	5000.0	1,060,000.0	3703.7	785,185.2	
Aug 2007	5000.0	1,215,000.0	3703.7	900,000.0	
Sep 2007	5000.0	1,365,000.0	3703.7	1,011,111.1	
Oct 2007	5000.0	1,520,000.0	3703.7	1,125,925.9	
Nov 2007	5000.0	1,670,000.0	3703.7	1,237,037.0	
Dec 2007	5000.0	1,825,000.0	3703.7	1,351,851.9	
Jan 2008	5000.0	1,980,000.0	3703.7	1,466,666.7	
Feb 2008	5000.0	2,125,000.0	3703.7	1,574,074.1	
Mar 2008	5000.0	2,280,000.0	3703.7	1,688,888.9	
Apr 2008	5000.0	2,430,000.0	3703.7	1,800,000.0	
May 2008	5000.0	2,585,000.0	3703.7	1,914,814.8	
Jun 2008	5000.0	2,735,000.0	3703.7	2,025,925.9	
Jul 2008	5000.0	2,890,000.0	3703.7	2,140,740.7	
Aug 2008	5000.0	3,045,000.0	3703.7	2,255,555.6	
Sep 2008	5000.0	3,195,000.0	3703.7	2,366,666.7	
Oct 2008	5000.0	3,350,000.0	3703.7	2,481,481.5	
Nov 2008	5000.0	3,500,000.1	3127.6	2,575,308.5	
Dec 2008	5000.0	3,655,000.2	2686.0	2,658,574.6	

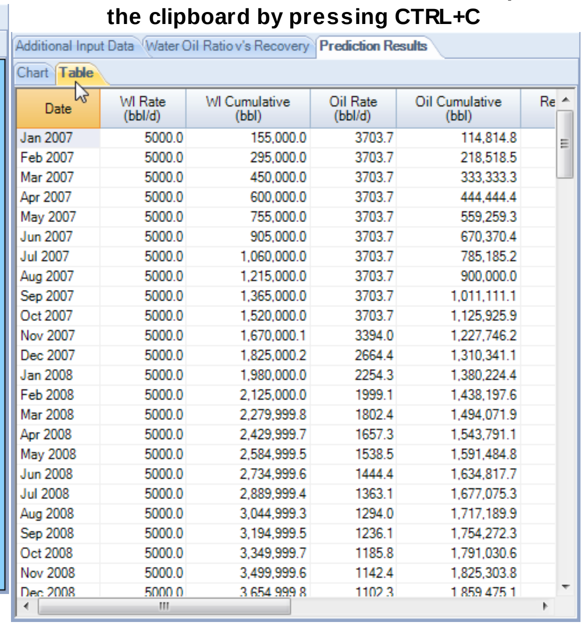
Extended Method Results

The Extended method results are also in the form of a WOR Vs oil recovery factory chart and table, together with a oil and water production profile and table.



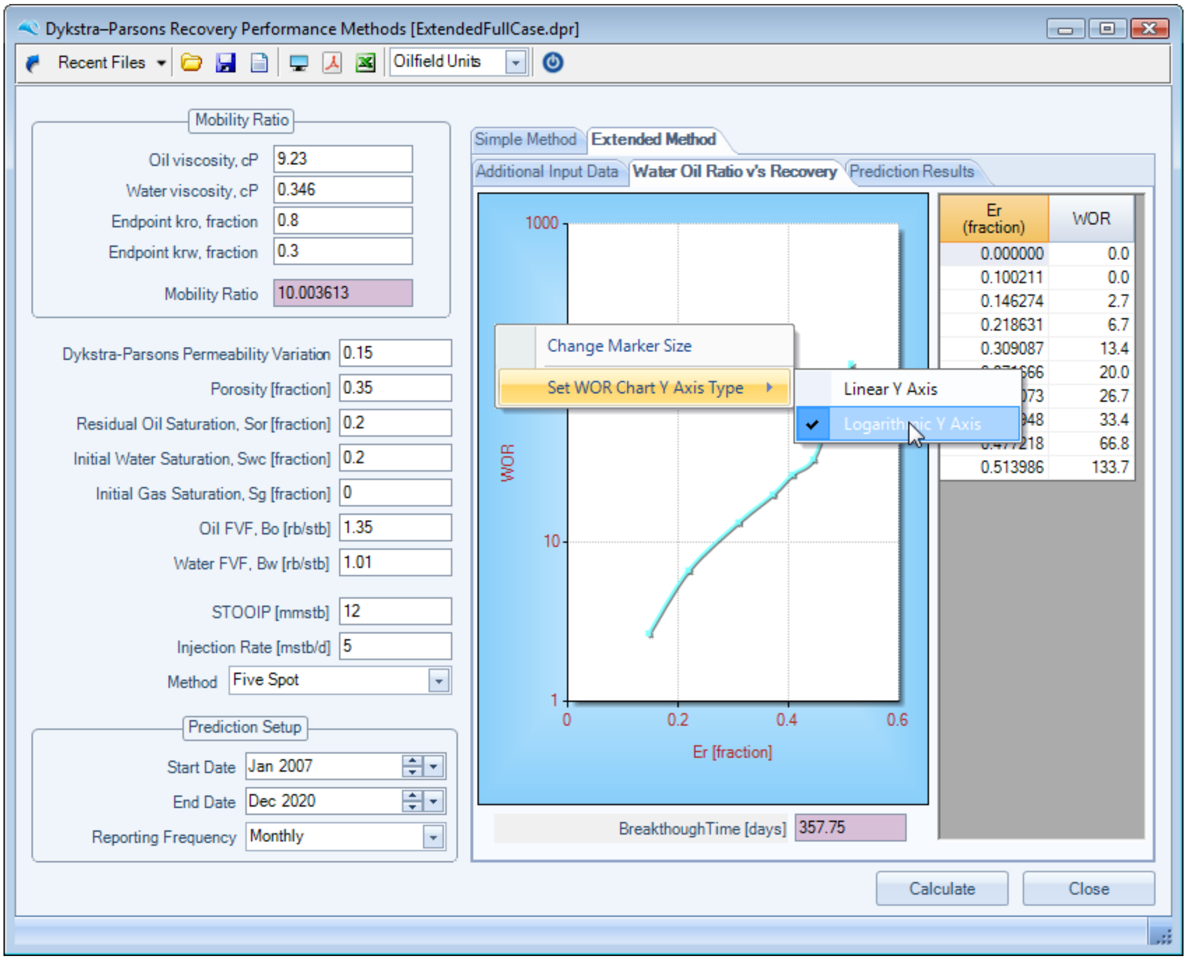
Note that all data within the tables can be output to the clipboard by pressing CTRL+C





Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Re
Jan 2007	5000.0	155,000.0	3703.7	114,814.8	
Feb 2007	5000.0	295,000.0	3703.7	218,518.5	
Mar 2007	5000.0	450,000.0	3703.7	333,333.3	
Apr 2007	5000.0	600,000.0	3703.7	444,444.4	
May 2007	5000.0	755,000.0	3703.7	559,259.3	
Jun 2007	5000.0	905,000.0	3703.7	670,370.4	
Jul 2007	5000.0	1,060,000.0	3703.7	785,185.2	
Aug 2007	5000.0	1,215,000.0	3703.7	900,000.0	
Sep 2007	5000.0	1,365,000.0	3703.7	1,011,111.1	
Oct 2007	5000.0	1,520,000.0	3703.7	1,125,925.9	
Nov 2007	5000.0	1,670,000.1	3394.0	1,227,746.2	
Dec 2007	5000.0	1,825,000.2	2664.4	1,310,341.1	
Jan 2008	5000.0	1,980,000.0	2254.3	1,380,224.4	
Feb 2008	5000.0	2,125,000.0	1999.1	1,438,197.6	
Mar 2008	5000.0	2,279,999.8	1802.4	1,494,071.9	
Apr 2008	5000.0	2,429,999.7	1657.3	1,543,791.1	
May 2008	5000.0	2,584,999.5	1538.5	1,591,484.8	
Jun 2008	5000.0	2,734,999.6	1444.4	1,634,817.7	
Jul 2008	5000.0	2,889,999.4	1363.1	1,677,075.3	
Aug 2008	5000.0	3,044,999.3	1294.0	1,717,189.9	
Sep 2008	5000.0	3,194,999.5	1236.1	1,754,272.3	
Oct 2008	5000.0	3,349,999.7	1185.8	1,791,030.6	
Nov 2008	5000.0	3,499,999.6	1142.4	1,825,303.8	
Dec 2008	5000.0	3,654,999.8	1102.3	1,859,475.1	

The user can also choose to display the Y axis of either the Simple or Extended WOR versus recovery factor charts as a logarithmic scale, in line with common industry practice. Simply press the right mouse button within a chart area, to display the chart's context menu list, and toggle between linear and logarithmic scales.



Part V

5 Log (Water Oil Ratio)

5.1 Log (WOR) Decline Forecasts

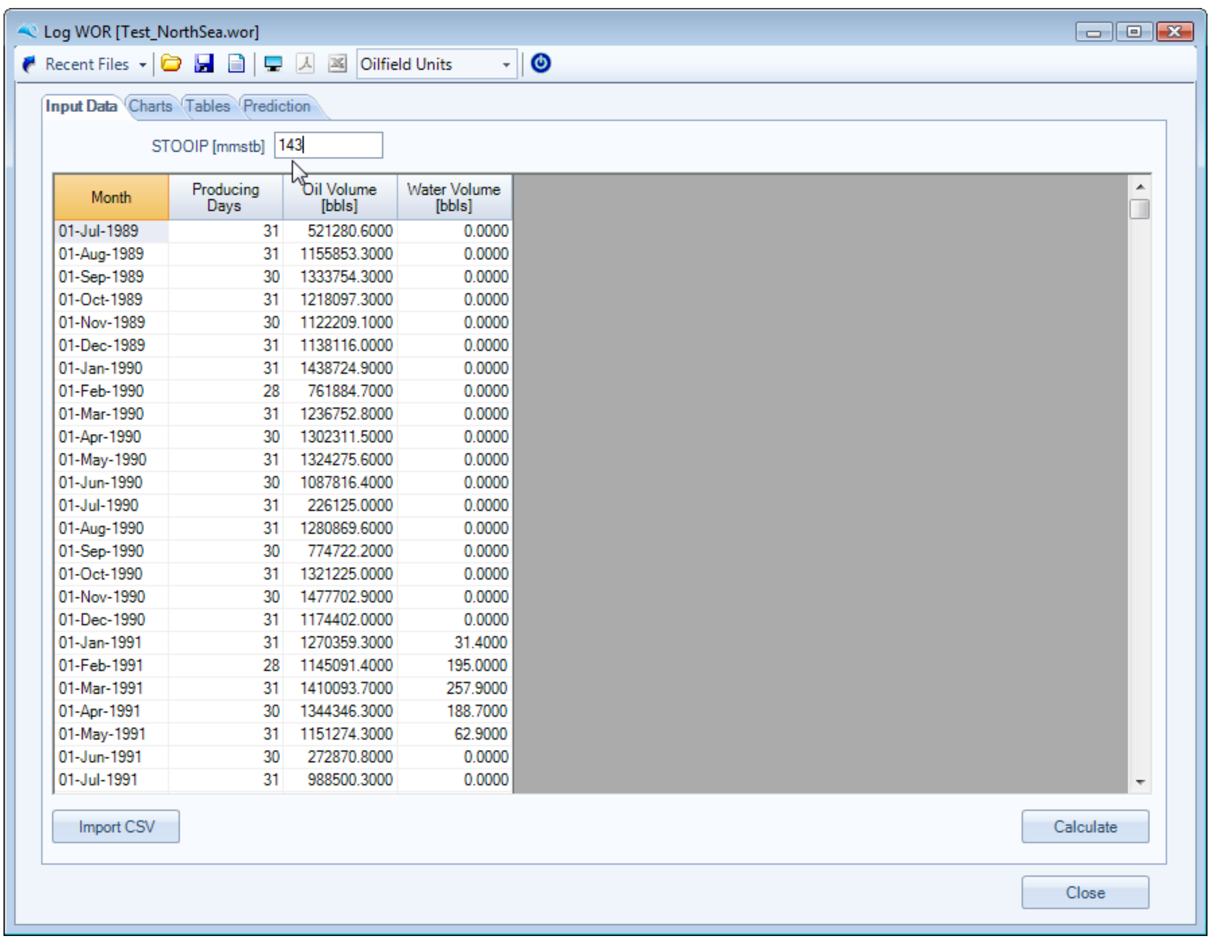
In terms of Waterdrive decline analysis, the Log(Water Oil Ratio) Vs Cumulative Oil Production (or Np) to predict oil recoveries for water oil ratios (WOR) greater than 1 or watercut greater than 50% is commonplace.

Therefore we have developed a simple routine to permit low, mid and high trend decline analysis of Log (WOR) Vs Np relationships. The user can also convert to an oil production rate Vs time series, by either assuming a starting oil rate or by a constant liquid production rate, which for steady state waterdrive fields is also a commonplace assumption.

The following series of screen captures describe how to use this workflow :

The user can copy and paste (via CTRL+C and CTRL+V) production data into the Input Data Table - just select the top left data cell as highlighted below, or choose to import data via the Import CSV button also shown below. The user can also choose to optionally input the Stock Tank Oil Originally in Place (STOOIP) and the application will automatically calculate recovery efficiencies versus time.

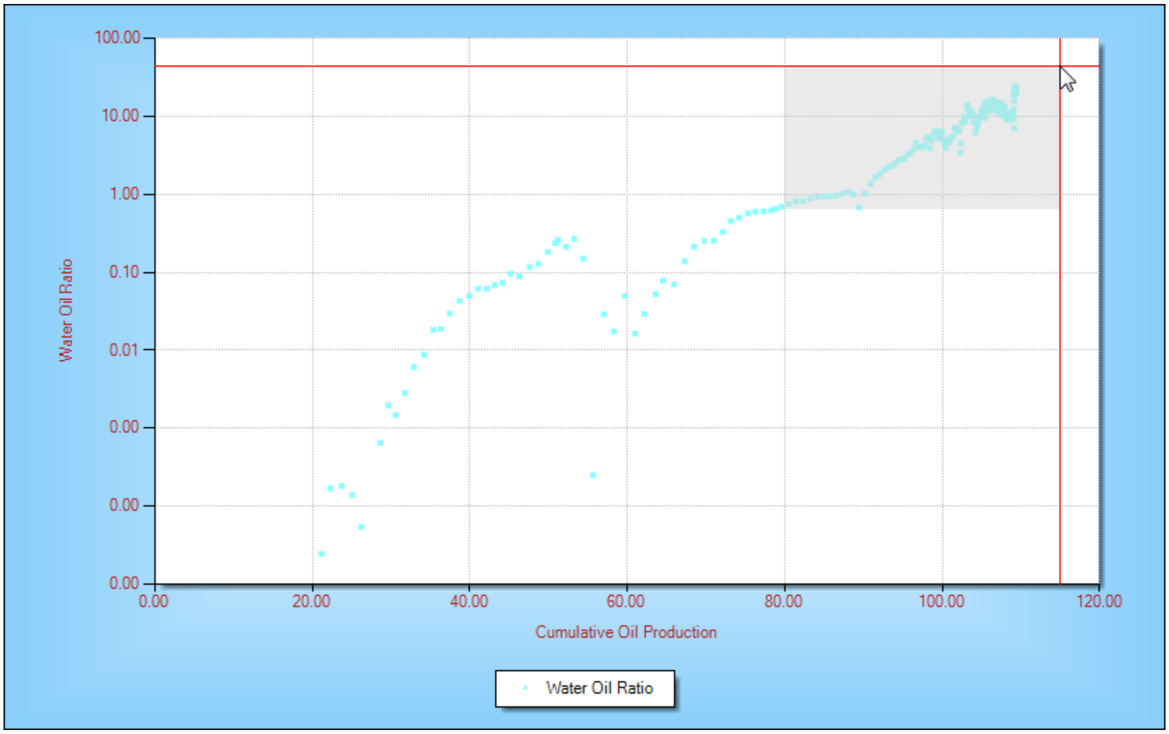
The historical data frequency used can be defined by the User, but we advise to input monthly production figures, as all of the prediction calculations are done with a monthly prediction frequency.



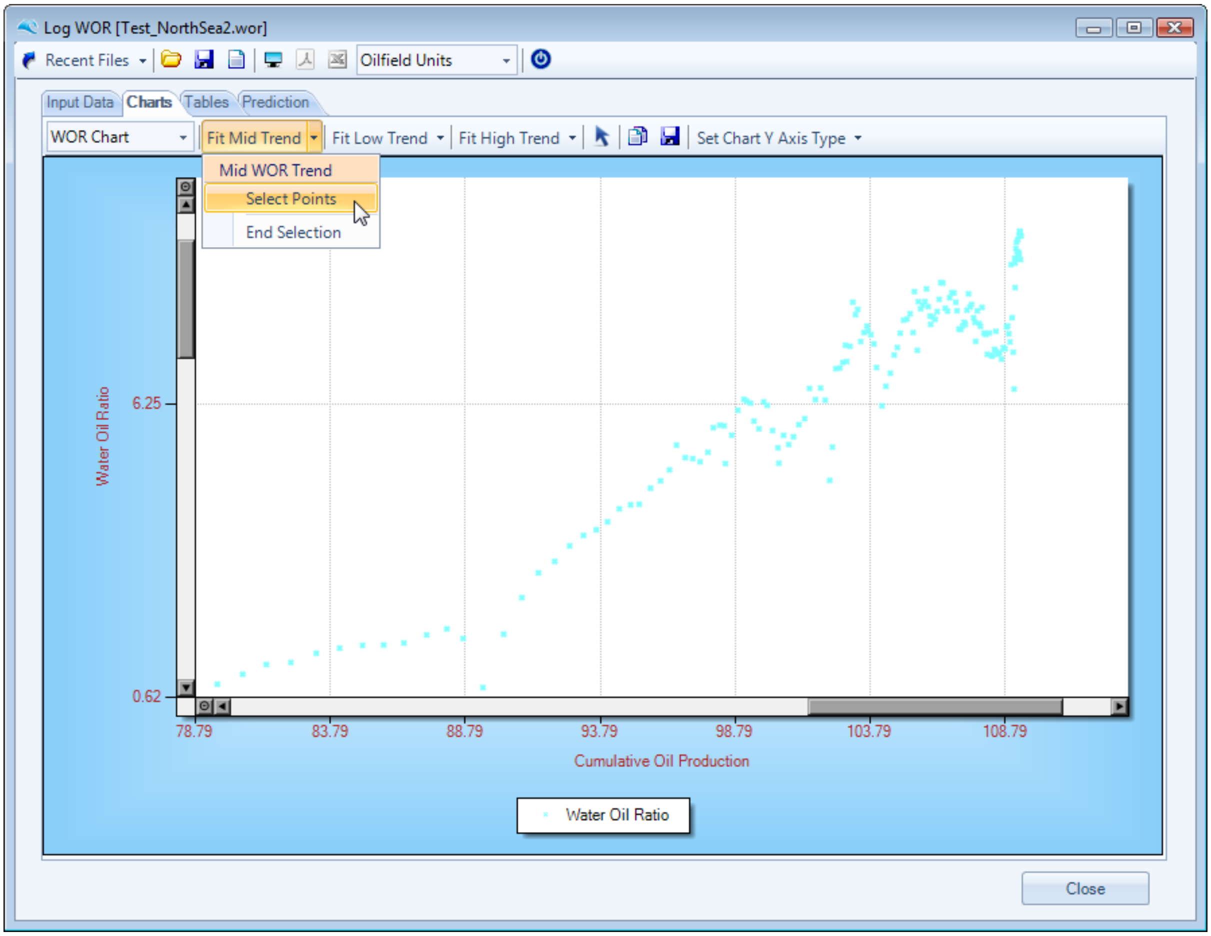
Month	Producing Days	Oil Volume [bbls]	Water Volume [bbls]
01-Jul-1989	31	521280.6000	0.0000
01-Aug-1989	31	1155853.3000	0.0000
01-Sep-1989	30	1333754.3000	0.0000
01-Oct-1989	31	1218097.3000	0.0000
01-Nov-1989	30	1122209.1000	0.0000
01-Dec-1989	31	1138116.0000	0.0000
01-Jan-1990	31	1438724.9000	0.0000
01-Feb-1990	28	761884.7000	0.0000
01-Mar-1990	31	1236752.8000	0.0000
01-Apr-1990	30	1302311.5000	0.0000
01-May-1990	31	1324275.6000	0.0000
01-Jun-1990	30	1087816.4000	0.0000
01-Jul-1990	31	226125.0000	0.0000
01-Aug-1990	31	1280869.6000	0.0000
01-Sep-1990	30	774722.2000	0.0000
01-Oct-1990	31	1321225.0000	0.0000
01-Nov-1990	30	1477702.9000	0.0000
01-Dec-1990	31	1174402.0000	0.0000
01-Jan-1991	31	1270359.3000	31.4000
01-Feb-1991	28	1145091.4000	195.0000
01-Mar-1991	31	1410093.7000	257.9000
01-Apr-1991	30	1344346.3000	188.7000
01-May-1991	31	1151274.3000	62.9000
01-Jun-1991	30	272870.8000	0.0000
01-Jul-1991	31	988500.3000	0.0000

Once the production data has been successfully input, the user should press the Calculate Button, as shown above, to populate the calculation Table and Chart.

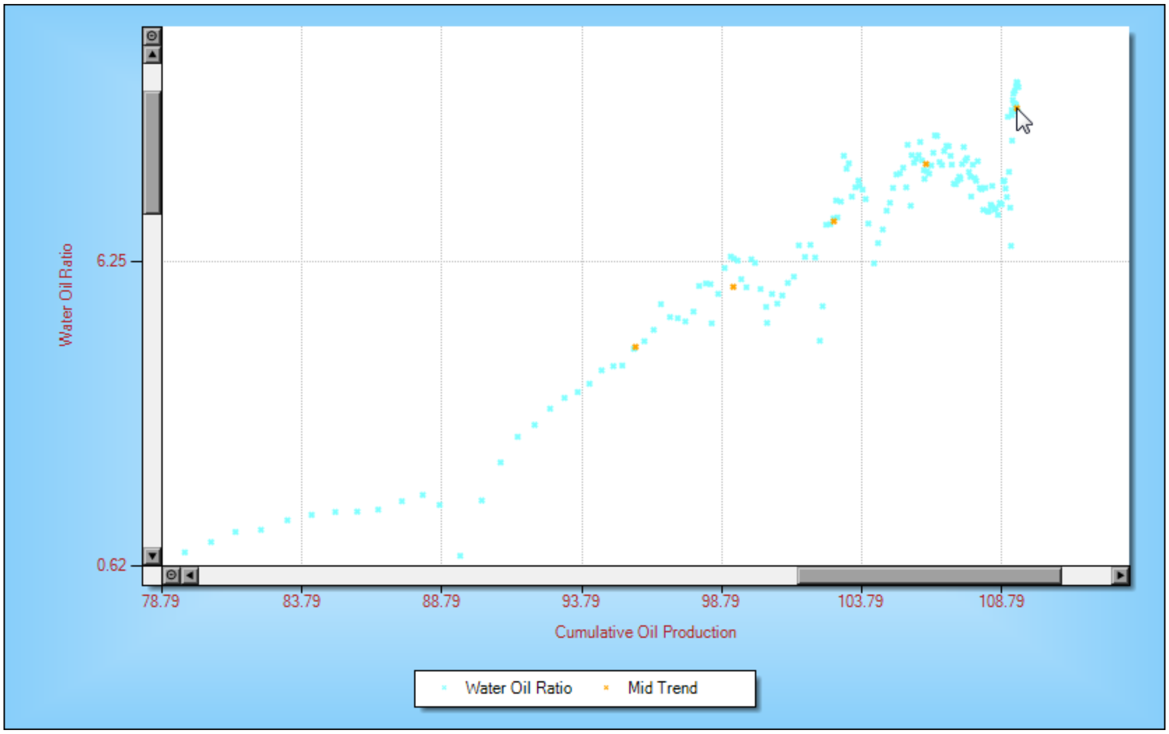
On the Charts Tab the following Log(WOR) Vs Cumulative Oil Production chart is displayed. The user can choose to zoom into the display to better digitize points for curve fitting a linear relationship. This functionality is shown below and is enabled by left mouse clicking and dragging a highlighted box. Once happy with the selected area, unrelease the mouse button and the chart area will zoom in.



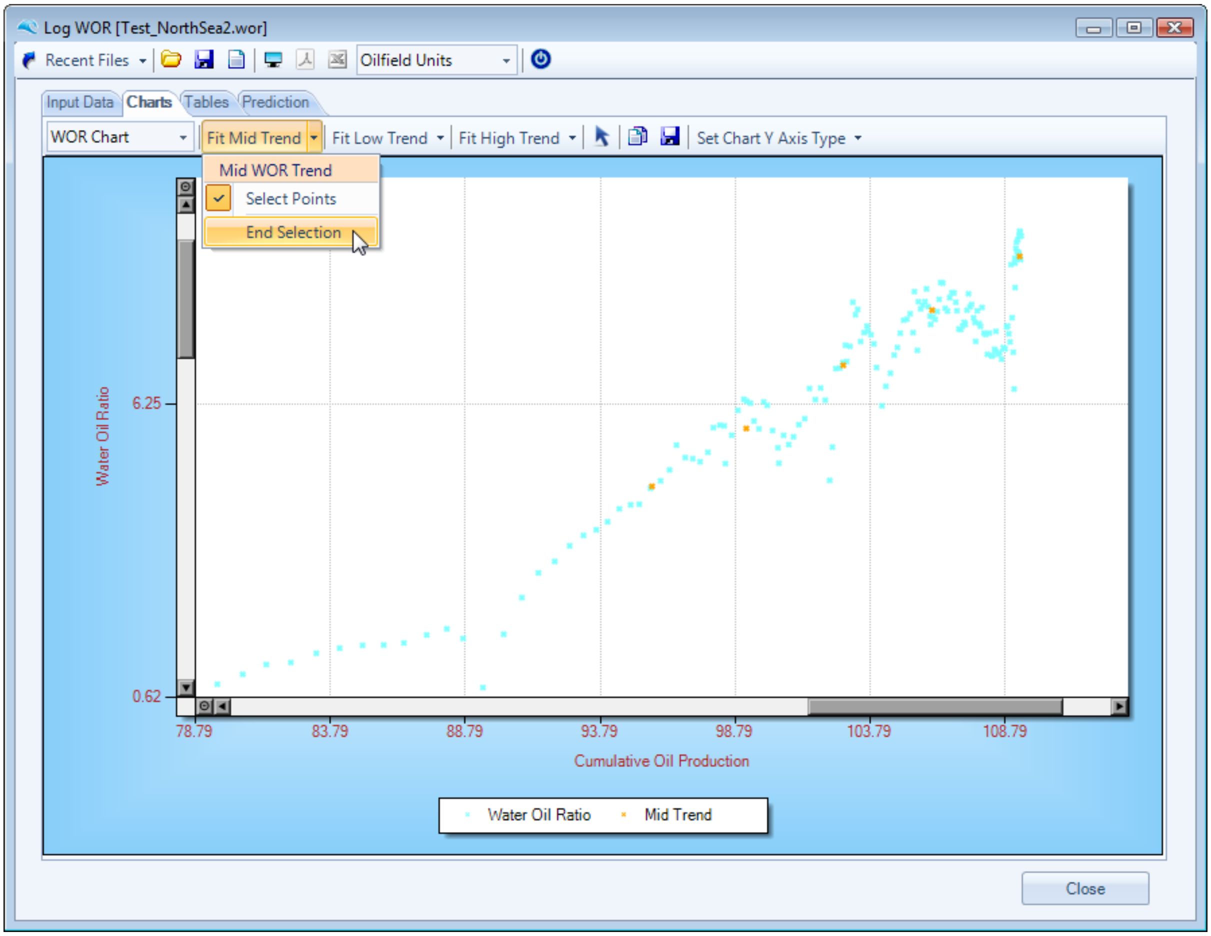
To select points to be fitted, select the Select Points button as shown below for the Fit Mid Trend. The process can be repeated for the Low and High trend analysis.

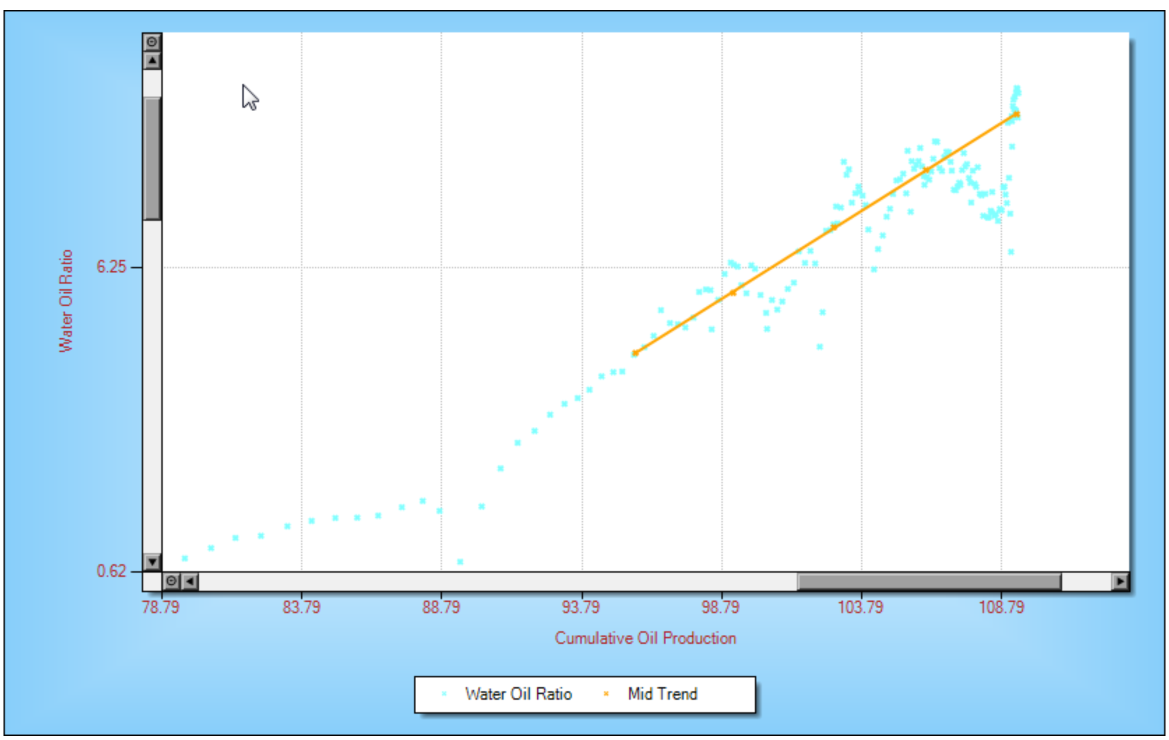


Once the Select Points button has been selected and highlighted, the user can select points directly in the chart area, by a series of single right mouse clicks, as shown below.

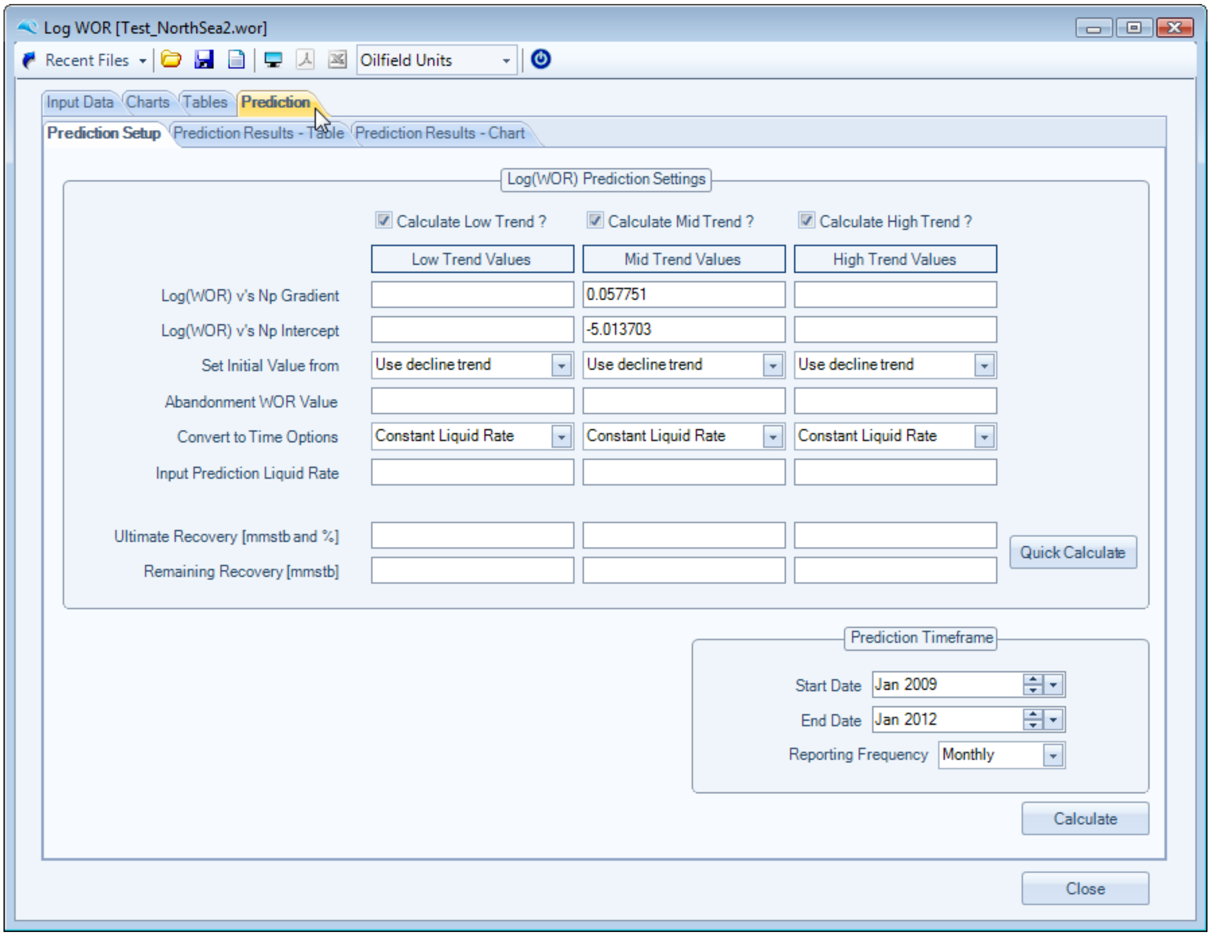


Once all of the required points have been selected, select the End Selection button, to fit a straight line through the selected points, as shown below.

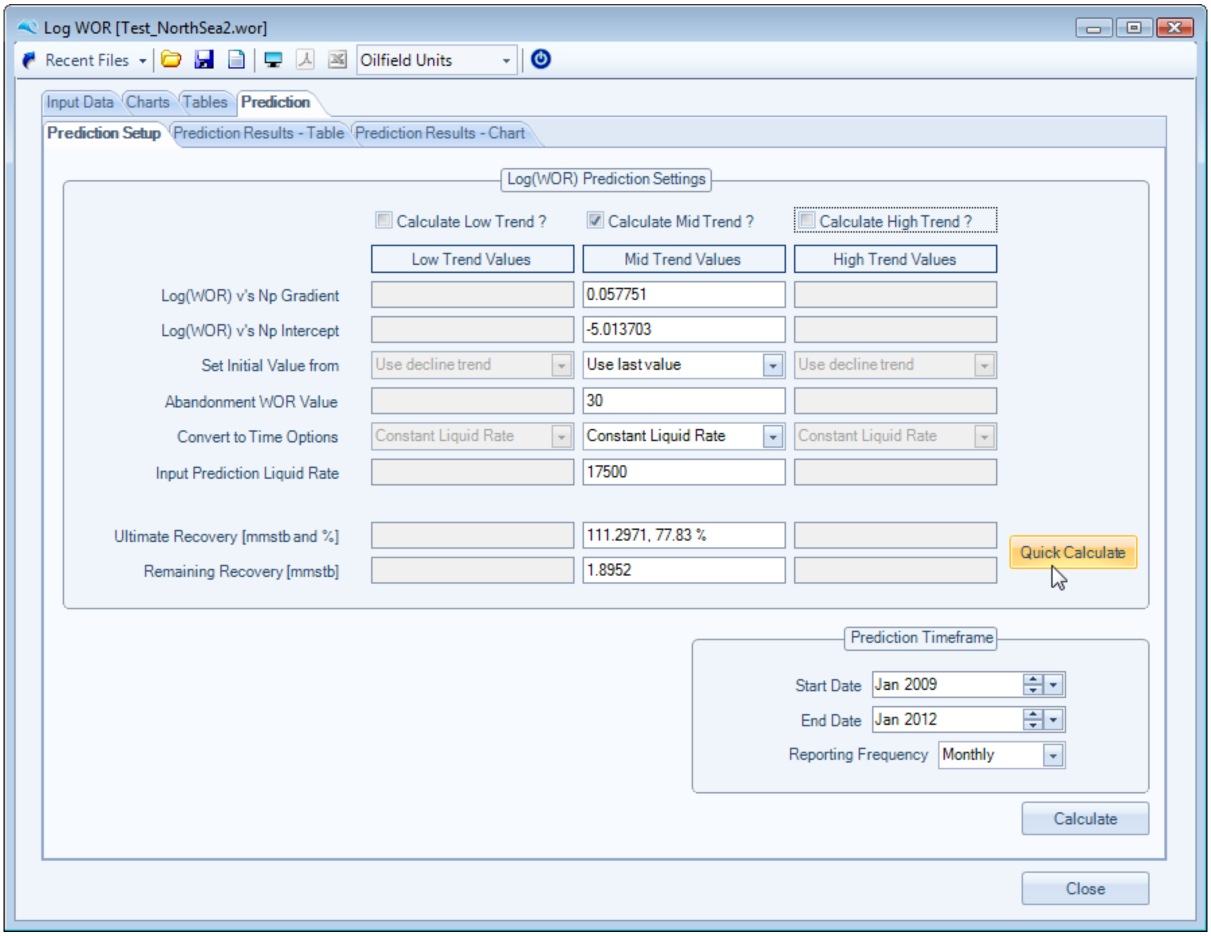

Log WOR [Test_NorthSea2.wor]
Recent Files
Oilfield Units
Input Data
Charts
Tables
Prediction
WOR Chart
Fit Mid Trend
Fit Low Trend
Fit High Trend
Set Chart Y Axis Type
Mid WOR Trend
Select Points
End Selection
Water Oil Ratio
6.25
0.62
78.79
83.79
88.79
93.79
98.79
103.79
108.79
Cumulative Oil Production
Water Oil Ratio
Mid Trend
Close


Water Oil Ratio
6.25
0.62
78.79
83.79
88.79
93.79
98.79
103.79
108.79
Cumulative Oil Production
Water Oil Ratio
Mid Trend

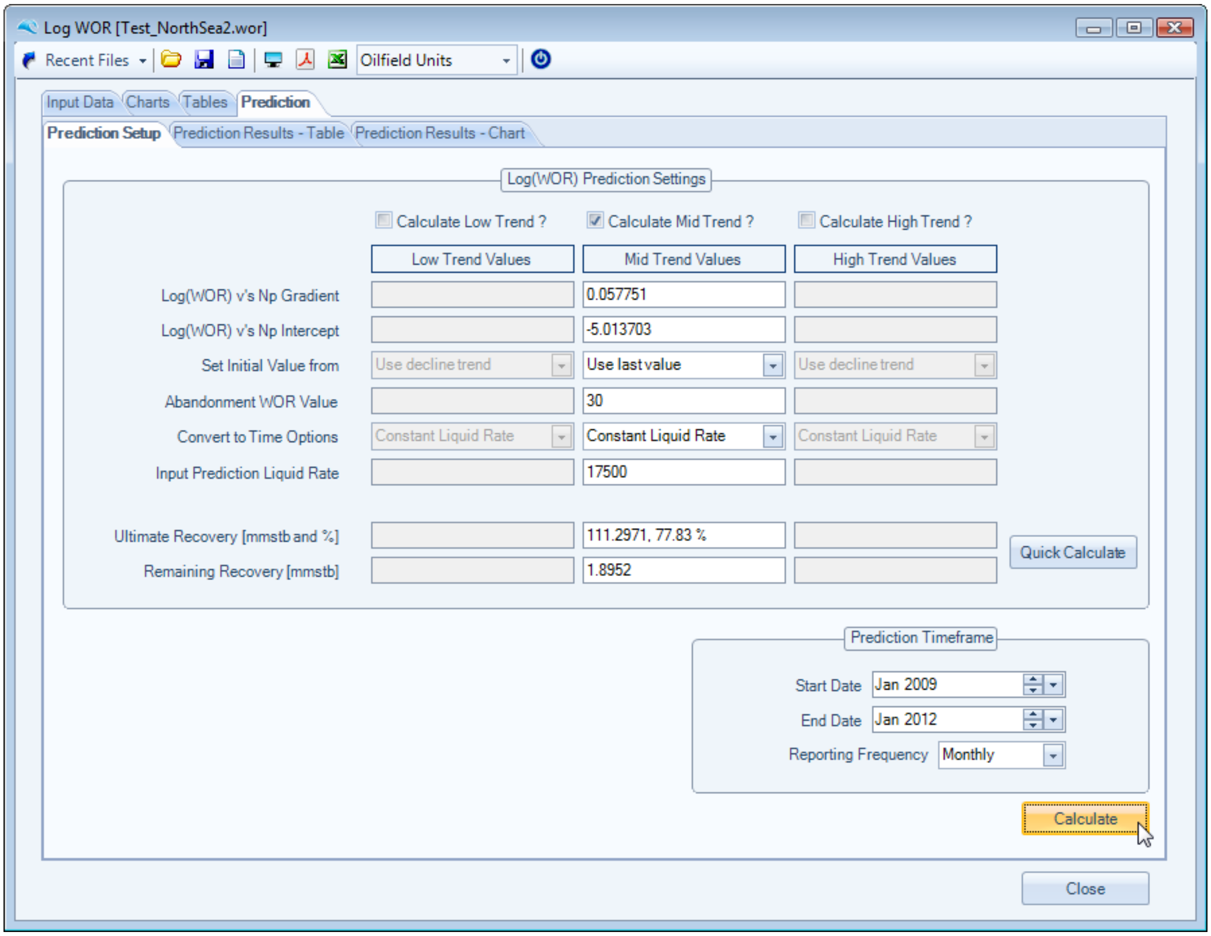
Once a straight line has been fitted through through the selected points, the User can see the Gradient and Intercept values associated with the straight line in the Prediction Tab, as shown below.



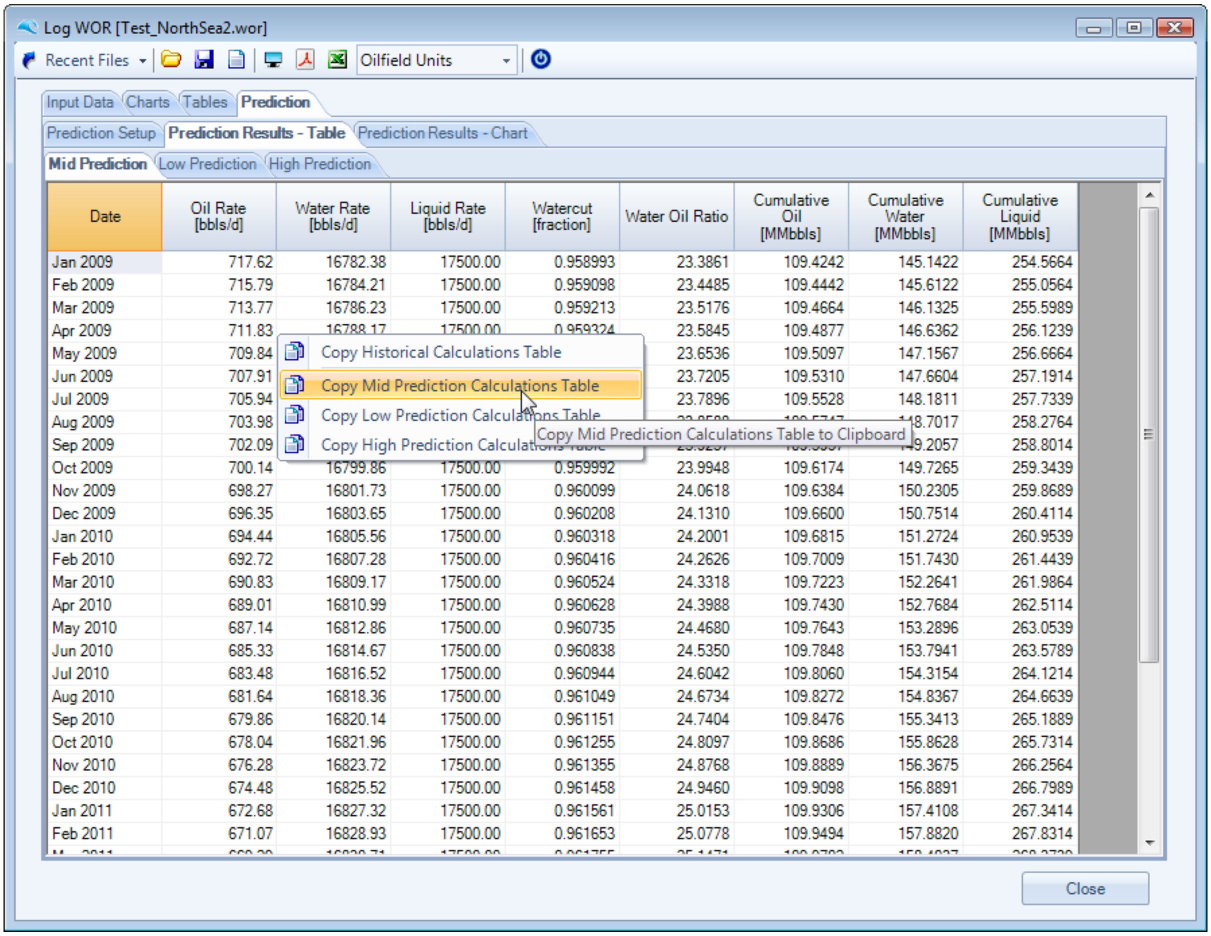
To convert to time or quickly calculate Ultimate and remaining recovery, the user should input Abandonment assumptions for Water Oil ratio and select how to convert to time, as shown below. The Quick Calculate button only uses the fitted linear relationship and intersects this with the Abandonment WOR value.



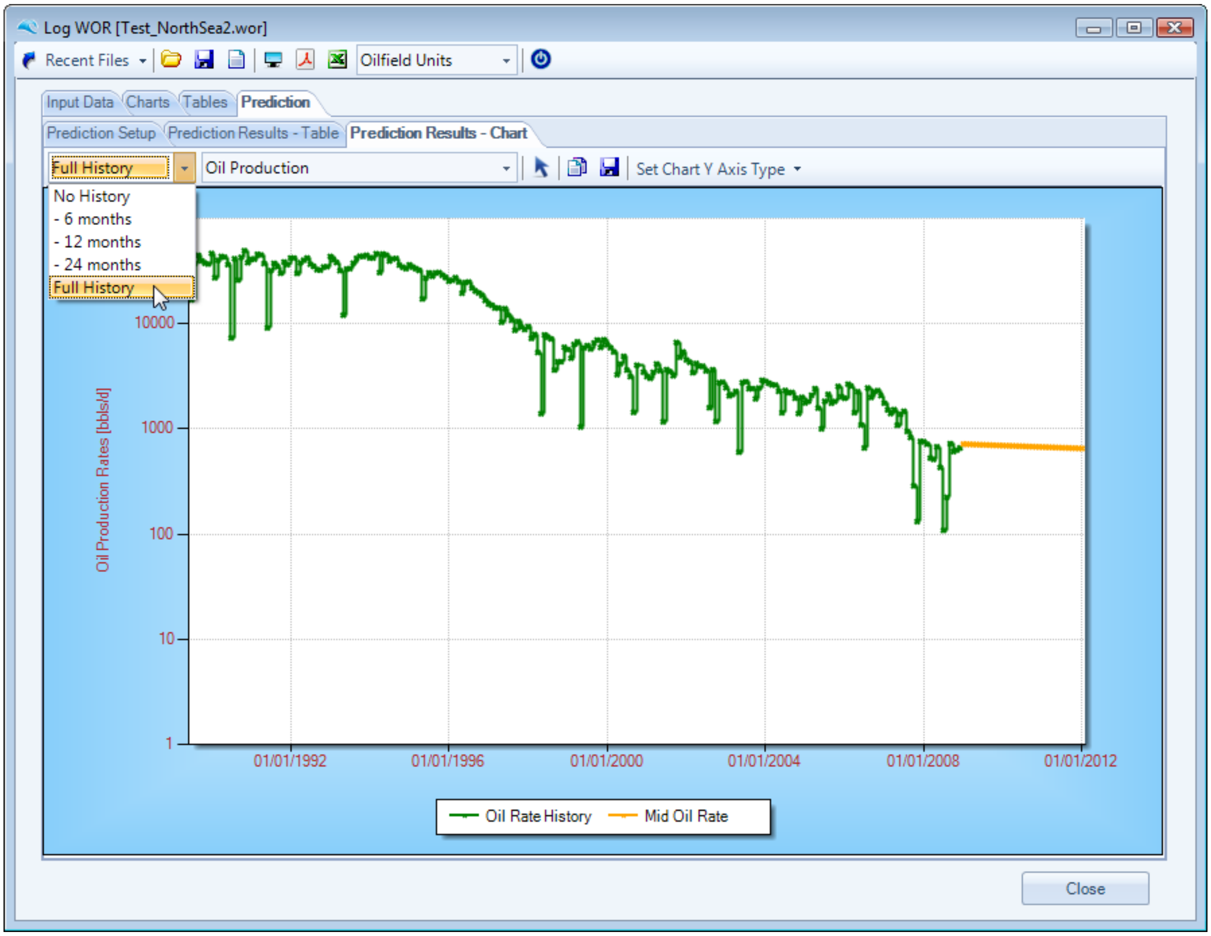
To convert the prediction to time, the user also needs to enter the start date, end date and reporting frequency. All internal calculations are done monthly, however the user can choose to report either monthly, semi annually or annually. This is shown for illustration purposes below :

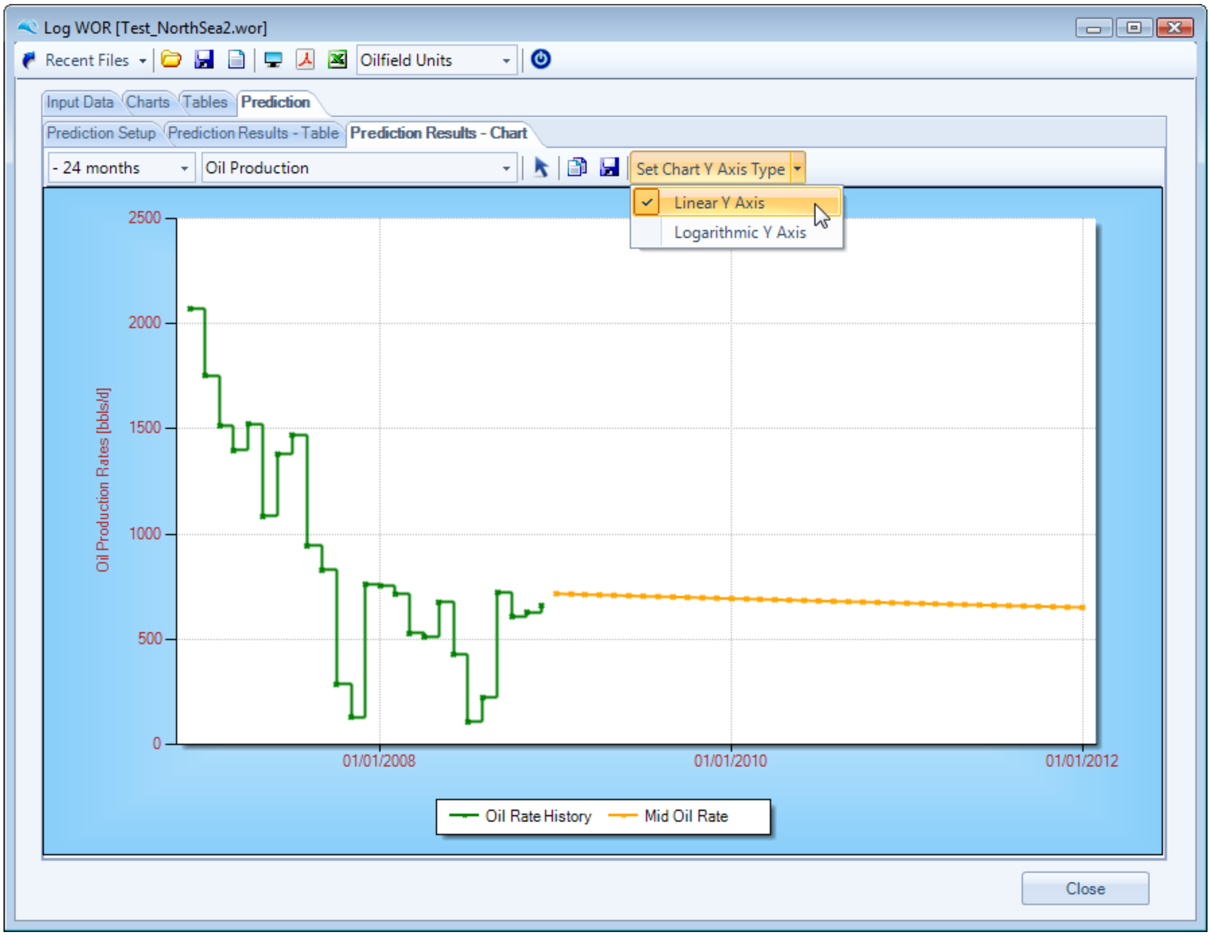


Once the user enters the prediction input correctly and presses the Calculate button, as shown above, the Prediction tables and Charts are populated. The User can copy the Table data from the application by a single right mouse click, to select the table Context menus. as shown below :

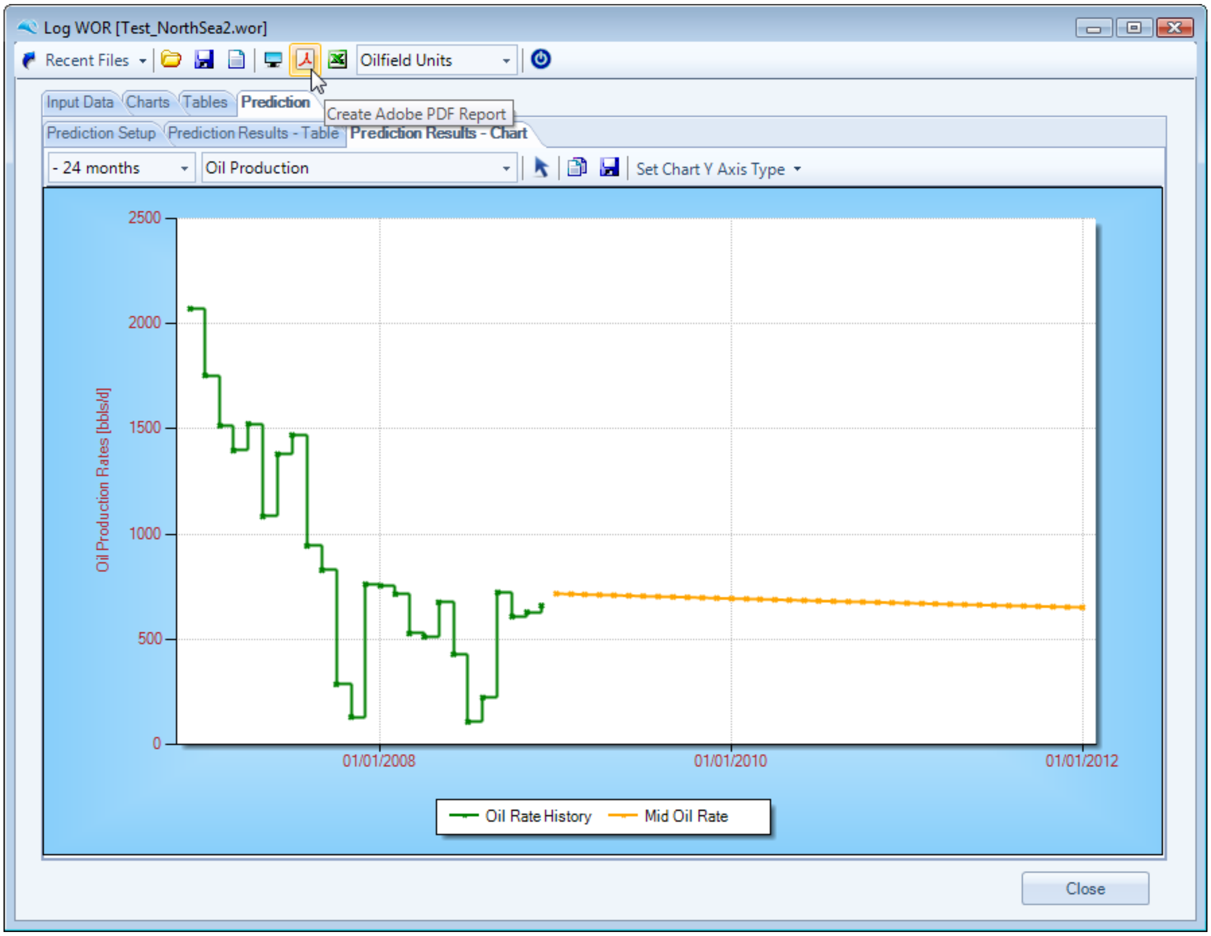


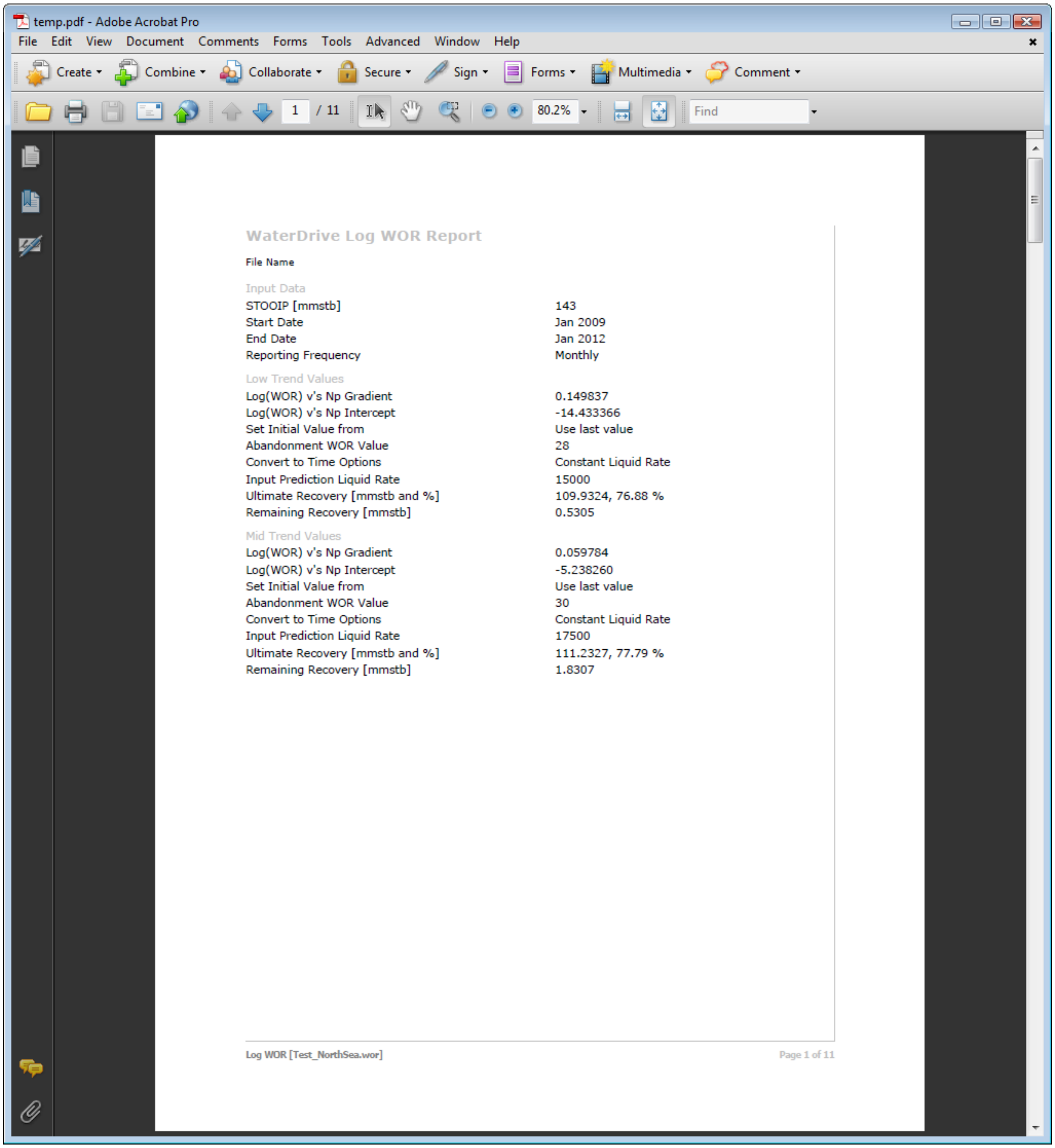
Various display elements of the prediction chart can be changed for both historical production, prediction phase (either Oil, Water or Total Liquids) and Y Axis type, see below :


Log WOR [Test_NorthSea2.wor]
Recent Files
Oilfield Units
Input Data
Charts
Tables
Prediction
Prediction Setup
Prediction Results - Table
Prediction Results - Chart
Full History
Oil Production
Set Chart Y Axis Type
No History
- 6 months
- 12 months
- 24 months
Full History
Oil Production Rates [bbls/d]
10000
1000
100
10
1
01/01/1992
01/01/1996
01/01/2000
01/01/2004
01/01/2008
01/01/2012
Oil Rate History
Mid Oil Rate
Close



Once happy with the prediction sensitivities, the user can create either Adobe PDF or Microsoft Excel reports, as depicted below :


Log WOR [Test_NorthSea2.wor]
Recent Files
Oilfield Units
Create Adobe PDF Report
Input Data
Charts
Tables
Prediction
Prediction Setup
Prediction Results - Table
Prediction Results - Chart
- 24 months
Oil Production
Set Chart Y Axis Type
Oil Production Rates [bbls/d]
2500
2000
1500
1000
500
0
01/01/2008
01/01/2010
01/01/2012
Oil Rate History
Mid Oil Rate
Close



WaterDrive Log WOR Report

File Name

Input Data

STOOIP [mmstb]	143
Start Date	Jan 2009
End Date	Jan 2012
Reporting Frequency	Monthly

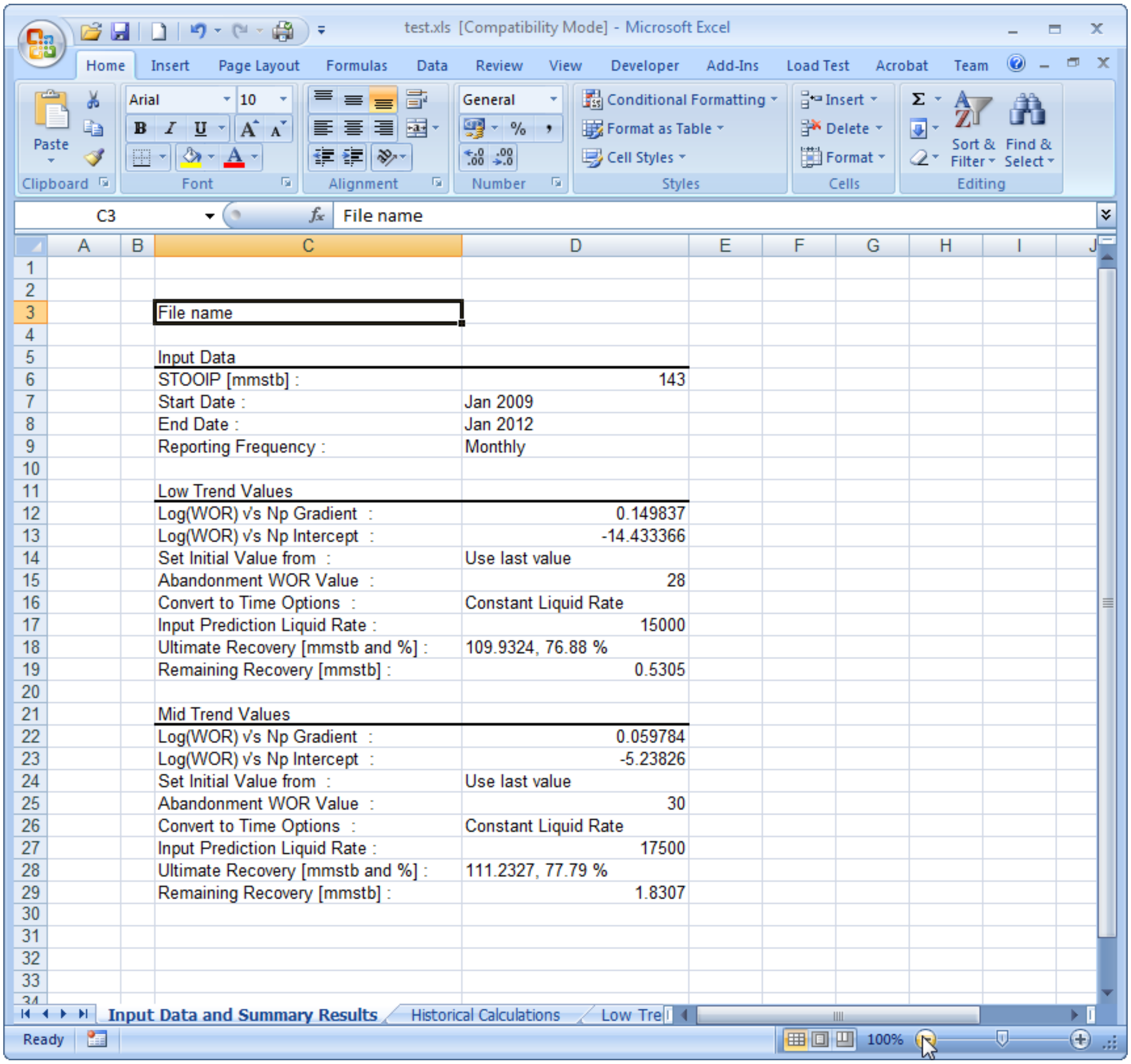
Low Trend Values

Log(WOR) v's Np Gradient	0.149837
Log(WOR) v's Np Intercept	-14.433366
Set Initial Value from	Use last value
Abandonment WOR Value	28
Convert to Time Options	Constant Liquid Rate
Input Prediction Liquid Rate	15000
Ultimate Recovery [mmstb and %]	109.9324, 76.88 %
Remaining Recovery [mmstb]	0.5305

Mid Trend Values

Log(WOR) v's Np Gradient	0.059784
Log(WOR) v's Np Intercept	-5.238260
Set Initial Value from	Use last value
Abandonment WOR Value	30
Convert to Time Options	Constant Liquid Rate
Input Prediction Liquid Rate	17500
Ultimate Recovery [mmstb and %]	111.2327, 77.79 %
Remaining Recovery [mmstb]	1.8307

Log WOR [Test_NorthSea.wor] Page 1 of 11


test.xls [Compatibility Mode] - Microsoft Excel
C3
File name
File name
Input Data
STOOIP [mmstb] : 143
Start Date : Jan 2009
End Date : Jan 2012
Reporting Frequency : Monthly
Low Trend Values
Log(WOR) V's Np Gradient : 0.149837
Log(WOR) V's Np Intercept : -14.433366
Set Initial Value from : Use last value
Abandonment WOR Value : 28
Convert to Time Options : Constant Liquid Rate
Input Prediction Liquid Rate : 15000
Ultimate Recovery [mmstb and %] : 109.9324, 76.88 %
Remaining Recovery [mmstb] : 0.5305
Mid Trend Values
Log(WOR) V's Np Gradient : 0.059784
Log(WOR) V's Np Intercept : -5.23826
Set Initial Value from : Use last value
Abandonment WOR Value : 30
Convert to Time Options : Constant Liquid Rate
Input Prediction Liquid Rate : 17500
Ultimate Recovery [mmstb and %] : 111.2327, 77.79 %
Remaining Recovery [mmstb] : 1.8307
Input Data and Summary Results
Historical Calculations
Low Tre
Ready
100%

Part VI

6 Water Coning

Production from an oil well creates a pressure gradient that tends to elevate the oil-water contact in the immediate vicinity of the well. Balancing this flowing gradient is the tendency of oil and water to maintain gravity equilibrium, owing to the density difference between the two fluids.

When the dynamic viscous forces at the well exceed gravitational forces, a water cone ultimate breaks through into the well perforations.

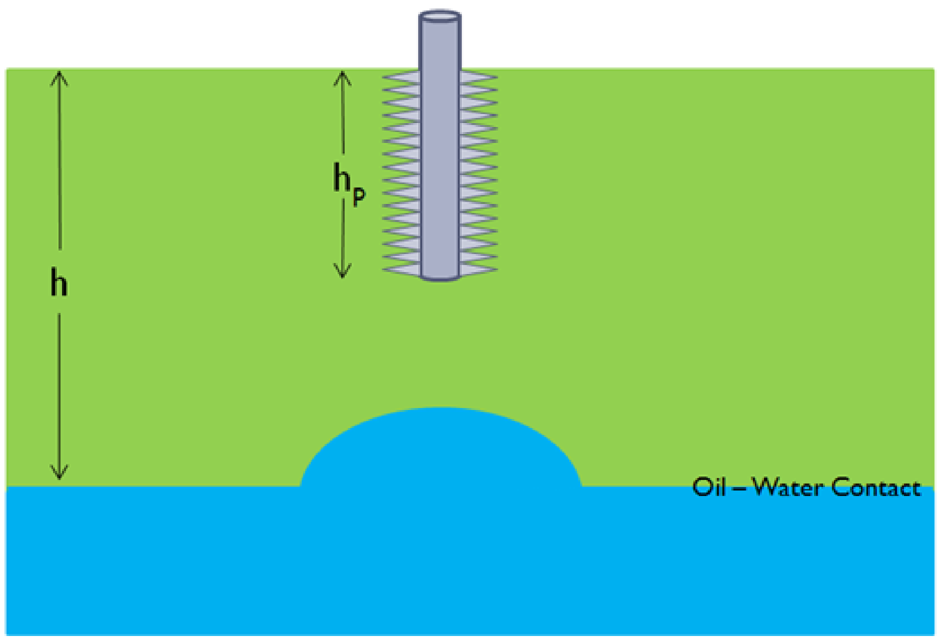
Critical rate is defined as the maximum allowable oil flow rate to avoid a water cone breaking through.

The coning problem for both vertical and horizontal wells typically involves the following calculations:

- Determination of the critical flow rate
- Breakthrough time predictions
- Well performance calculations after breakthrough

6.1 Vertical Wells

Several vertical well critical rate correlations are available in the literature, most of which are included within these routines.



In all of vertical well coning calculations the assumption is made that the perforations are always located at the top of the oil zone, thereby maximising the distance between the perforations and the oil-water contact.

It is important to note that these correlations are valid for a continuous oil pay zone with oil-water contact or gas-oil contact or both. These correlations show that the critical rate depends upon effective oil permeability, oil viscosity, density difference between oil and water or oil and gas, well penetration ratio, and vertical permeability.

The use of this routine is highlighted with the following example.

References:

Bournazel, C., and Jeanson, B., "*Fast Water Coning Evaluation*", SPE Paper 3628, 1971

Sobocinski, D. P., and Cornelius, A. J., "*A Correlation for Predicting Water Coning Time*", JPT, May 1965.

Kuo, C. T., and Desbrisay, C. L., "*A Simplified Method for Water Coning Predictions*", SPE Paper 12067, 1983

Hoyland, L. A., Papatzacos, P., and Skjaeveland, S. M., "*Critical Rate for Water Coning: Correlation and Analytical Solution*", SPE Paper 15855, 1989

Chierici, G. L., "*Principles of Petroleum Reservoir Engineering Volume 2*", Springer-Verlag 1994

Joshi, S., "*Horizontal Well Technology*", Pennwell, 1991

Chaperon, I., "*Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotrophic Formations: Subcritical and Critical Rates*", SPE Paper 15377, 1986.

Schols, R. S., "*An Empirical Formula for the Critical Oil Production Rate*", Erdoel Erdgas, January 1972

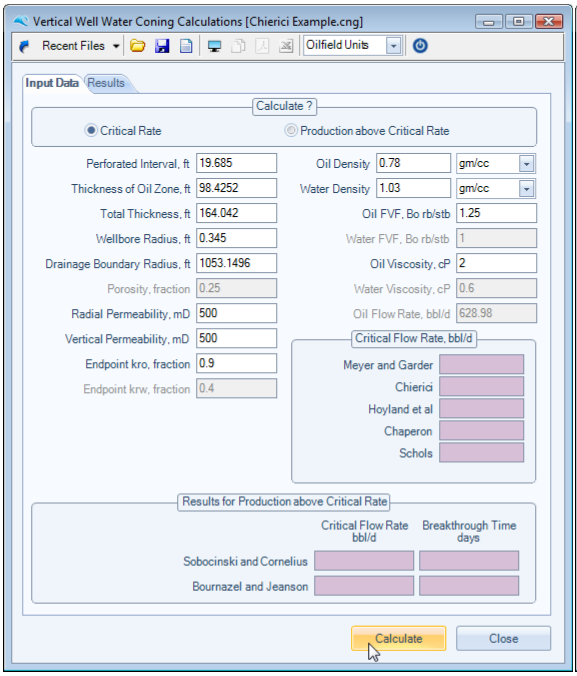
Meyer, H. I., and Garder, A. O., "*Mechanics of Two Immiscible Fluids in Porous Media*", J. Applied Physics, November 1954

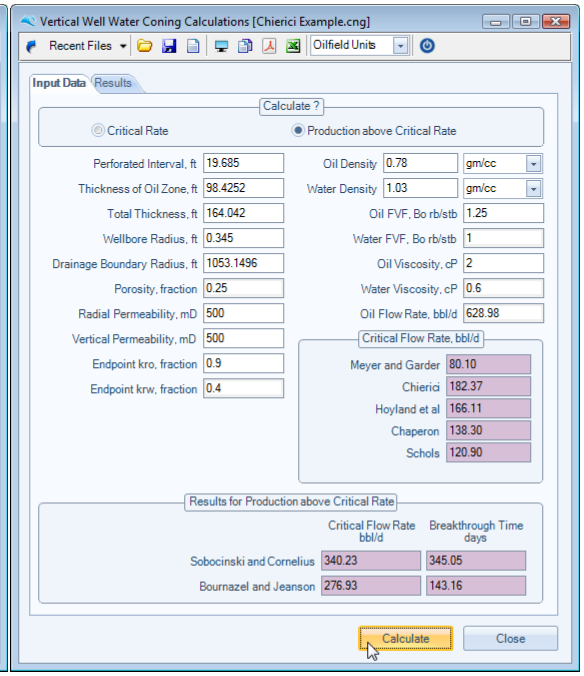
6.1.1 Example

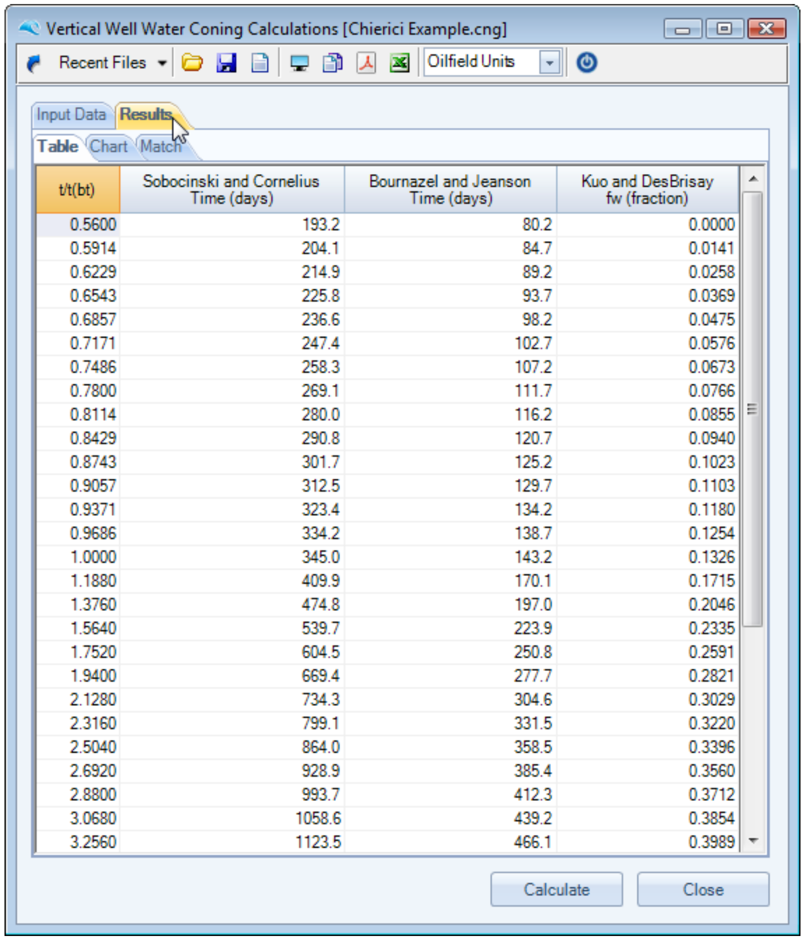
Chierici provides the following example in Chapter 12 of his textbook "Principles of Petroleum Reservoir Engineering Volume 2".

Input Data	
Perforated Interval, m	6
Thickness of Oil Zone, m	30
Total Thickness, m	50
Wellbore Radius, m	0.1052
Drainage Boundary Radius, m	321
Porosity, fraction	0.25
Radial Permeability, mD	500
Vertical Permeability, mD	500
kv/kh ratio	1
Endpoint kro, fraction	0.9
Endpoint krw, fraction	0.4
Oil Density, gm/cc	0.78
Water Density, gm/cc	1.03
Oil FVF, Bo rm^3/sm^3	1.25
Water FVF, Bo rm^3/sm^3	1
Oil Viscosity, cP	2
Water Viscosity, cP	0.6
Oil Flow Rate, m^3/d	100

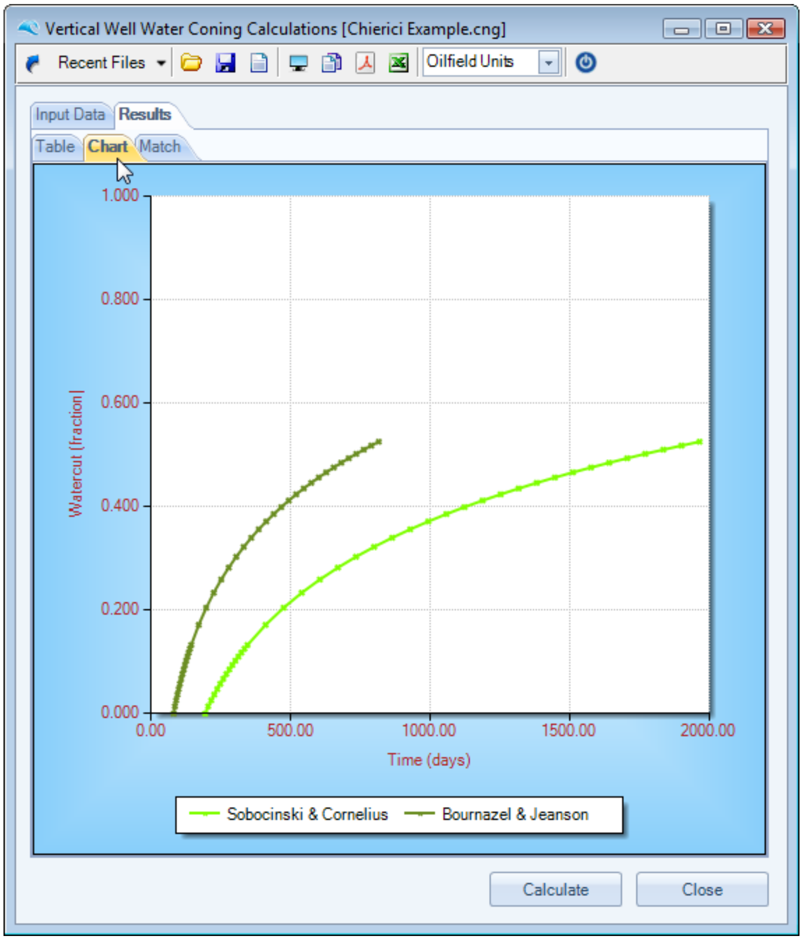
Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the ***calculate*** button to perform the coning calculations.

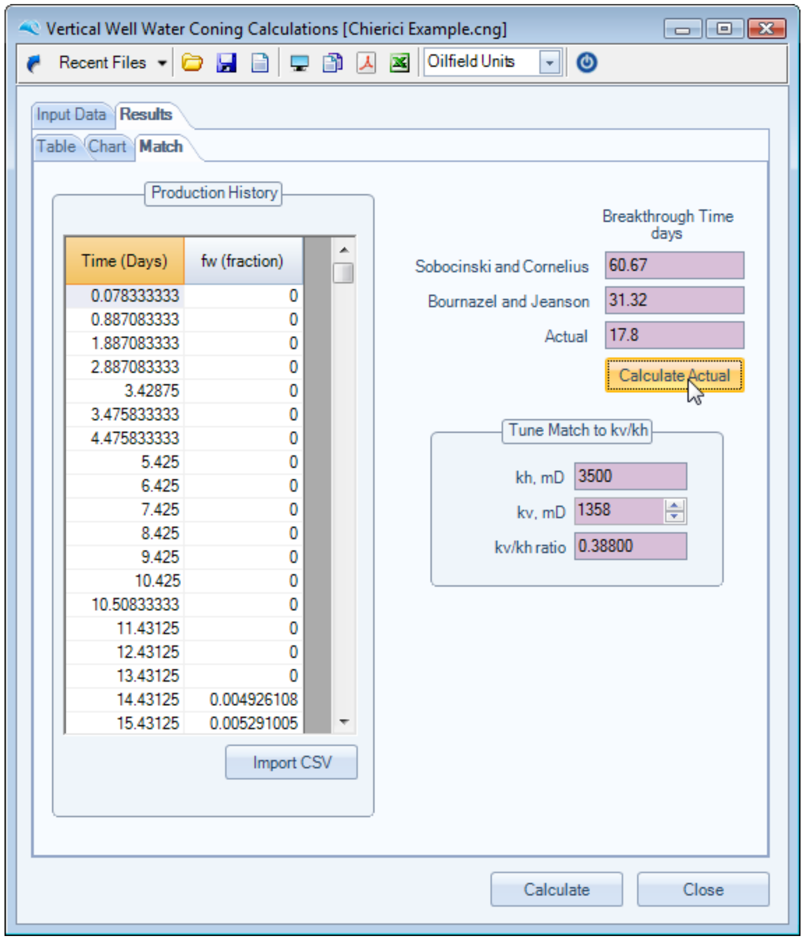




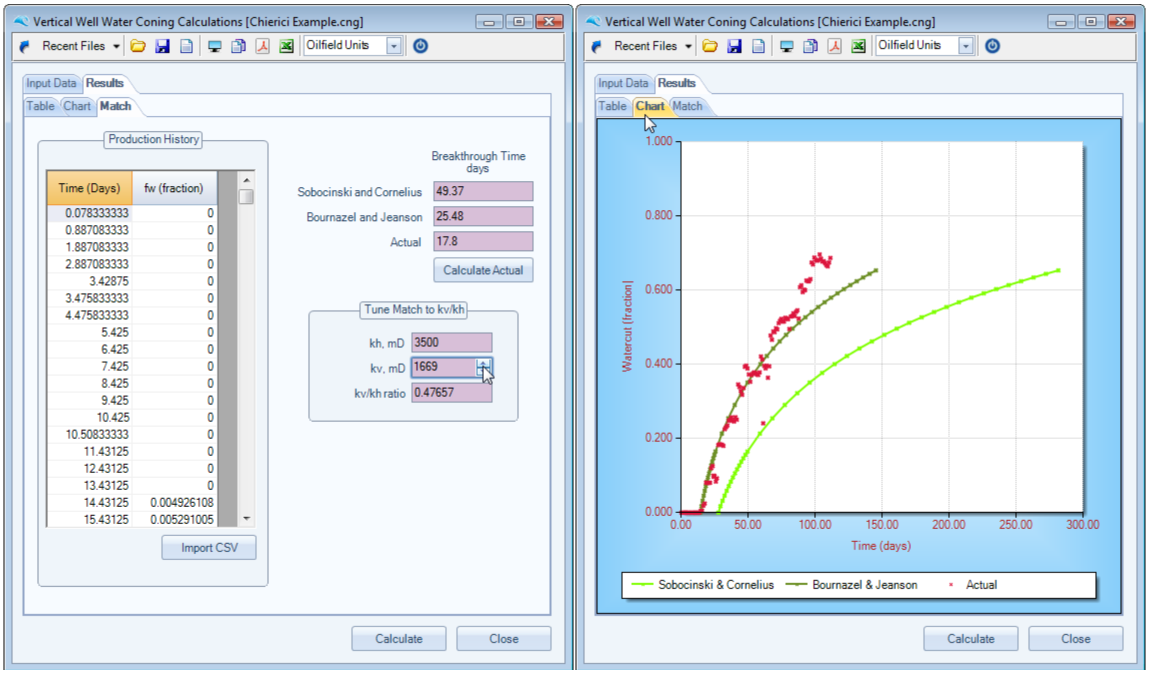


t/t(bt)	Sobocinski and Cornelius Time (days)	Bournazel and Jeanson Time (days)	Kuo and DesBrisay fw (fraction)
0.5600	193.2	80.2	0.0000
0.5914	204.1	84.7	0.0141
0.6229	214.9	89.2	0.0258
0.6543	225.8	93.7	0.0369
0.6857	236.6	98.2	0.0475
0.7171	247.4	102.7	0.0576
0.7486	258.3	107.2	0.0673
0.7800	269.1	111.7	0.0766
0.8114	280.0	116.2	0.0855
0.8429	290.8	120.7	0.0940
0.8743	301.7	125.2	0.1023
0.9057	312.5	129.7	0.1103
0.9371	323.4	134.2	0.1180
0.9686	334.2	138.7	0.1254
1.0000	345.0	143.2	0.1326
1.1880	409.9	170.1	0.1715
1.3760	474.8	197.0	0.2046
1.5640	539.7	223.9	0.2335
1.7520	604.5	250.8	0.2591
1.9400	669.4	277.7	0.2821
2.1280	734.3	304.6	0.3029
2.3160	799.1	331.5	0.3220
2.5040	864.0	358.5	0.3396
2.6920	928.9	385.4	0.3560
2.8800	993.7	412.3	0.3712
3.0680	1058.6	439.2	0.3854
3.2560	1123.5	466.1	0.3989


Vertical Well Water Coning Calculations [Chierici Example.cng]
Recent Files
Oilfield Units
Input Data
Results
Table
Chart
Match
1.000
0.800
0.600
0.400
0.200
0.000
Watercut [fraction]
0.00
500.00
1000.00
1500.00
2000.00
Time (days)
Sobocinski & Cornelius
Bournazel & Jeanson
Calculate
Close



With the above input panel, and a knowledge of production history (time in days and watercut), the user can iterate the vertical permeability to achieve an acceptable match. See example provided below.



6.2 Horizontal Wells

The use of horizontal well technology in developing hydrocarbon reservoirs have been widely applied during the 1990's, and subsequent years.

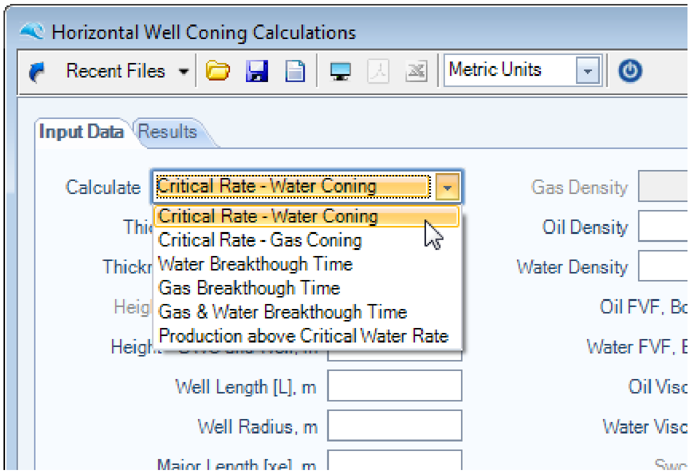
The advantages of using a horizontal well over a conventional vertical well are their larger capacity to produce oil for the same drawdown, together with a longer breakthrough time at a given production rate.

Several horizontal well critical rate correlations are available in the literature, most of which are included within these routines. The method of Kuo and Desbrisay has been used within this routine, for horizontal wells, to predict the performance after water breakthrough.

The list of routines available are :

- critical rate calculations for gas and water coning,
- breakthrough time calculation for both gas and water, and
- production performance above critical rate for water.

Accessing these routines is via a dropdown list box located towards the top of the application, as shown below.



References:

Chaperon, I., “Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotrophic Formations: Subcritical and Critical Rates,” *SPE Paper 15377*, 1986.

Efros, D. A., “Study of Multiphase Flows in Porous Media”, *Gastoptexizdat*, Leningrad, 1963.

Karcher, B., Giger, F., and Combe, J., “Some Practical Formulas to Predict Horizontal Well Behavior,” *SPE Paper 15430*, 1986

Joshi, S., "Horizontal Well Technology", *Pennwell*, 1991.

Ozkan, E., and Raghavan, R., “Performance of Horizontal Wells Subject to Bottom Water Drive,” *SPE Paper 18545*, 1988.

Papatzacos, P., Herring, T. U., Martinsen, R., and Skjaeveland, S. M., “Cone Breakthrough Time for Horizontal Wells,” *SPE Paper 19822*, 1989.

Kuo, C. T., and Desbrisay, C. L., "*A Simplified Method for Water Coning Predictions*", SPE Paper 12067, 1983

6.2.1 Example

Joshi provides several examples in Chapter 8 of his textbook "Horizontal Well Technology" that will be used to highlight various aspects of the calculations within these routines.

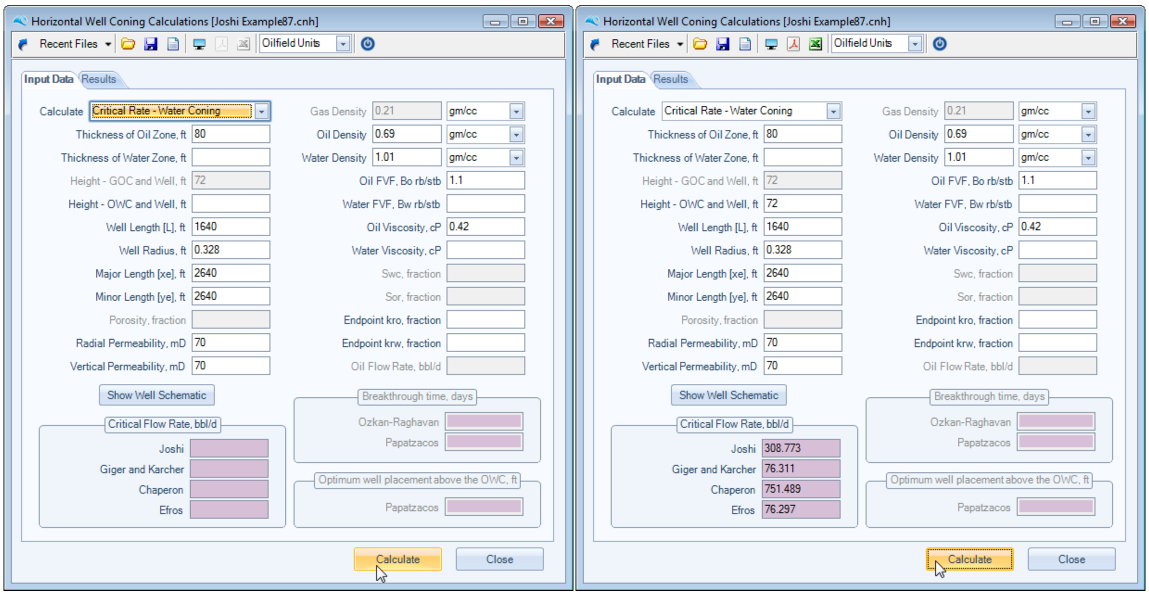
Critical Rate for Gas Coning

From Joshi's Example 8.7, the following data is provided and the Engineer is asked to calculate the critical rate for gas coning.

Input Data	
Thickness of Oil Zone, ft	80
Height - GOC and Well, ft	72
Well Length [L], ft	1640
Well Radius, ft	0.328

Major Length [xe], ft	2640
Minor Length [ye], ft	2640
Radial Permeability, mD	70
Vertical Permeability, mD	70
Gas Density, gm/cc	0.21
Oil Density, gm/cc	0.69
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.1
Oil Viscosity, cP	0.42

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the ***calculate*** button to perform the coning calculations.

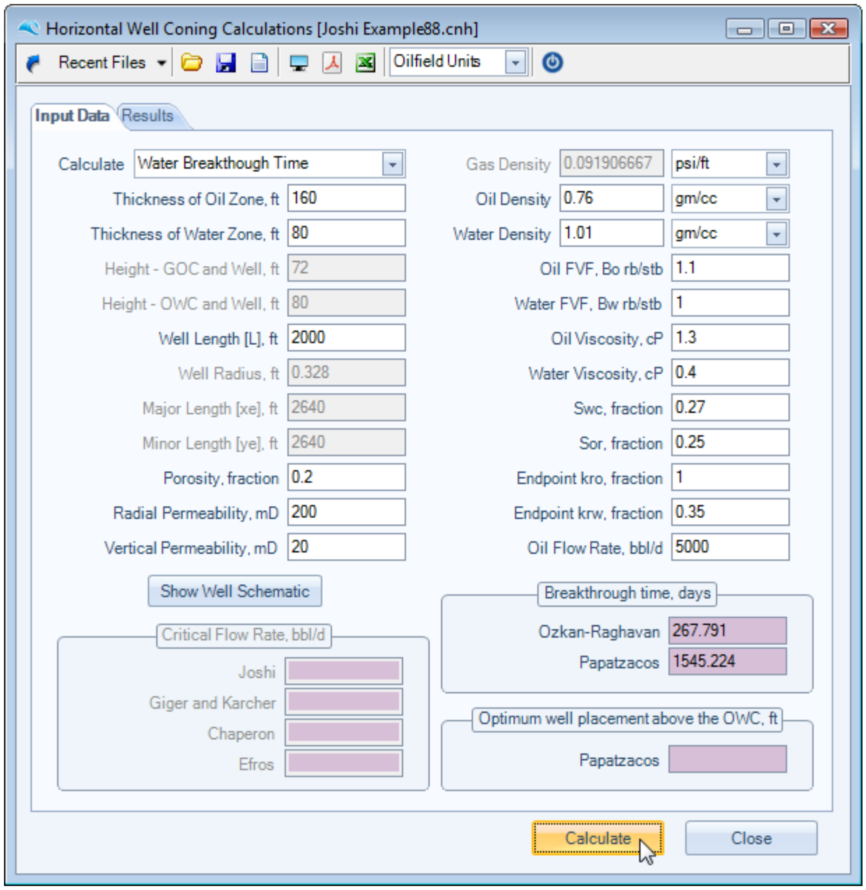


Water Breakthrough Time

From Joshi's Example 8.8, the following data is provided, and the Engineer is asked to calculate the water breakthrough time for a bottom waterdrive oil reservoir.

Input Data

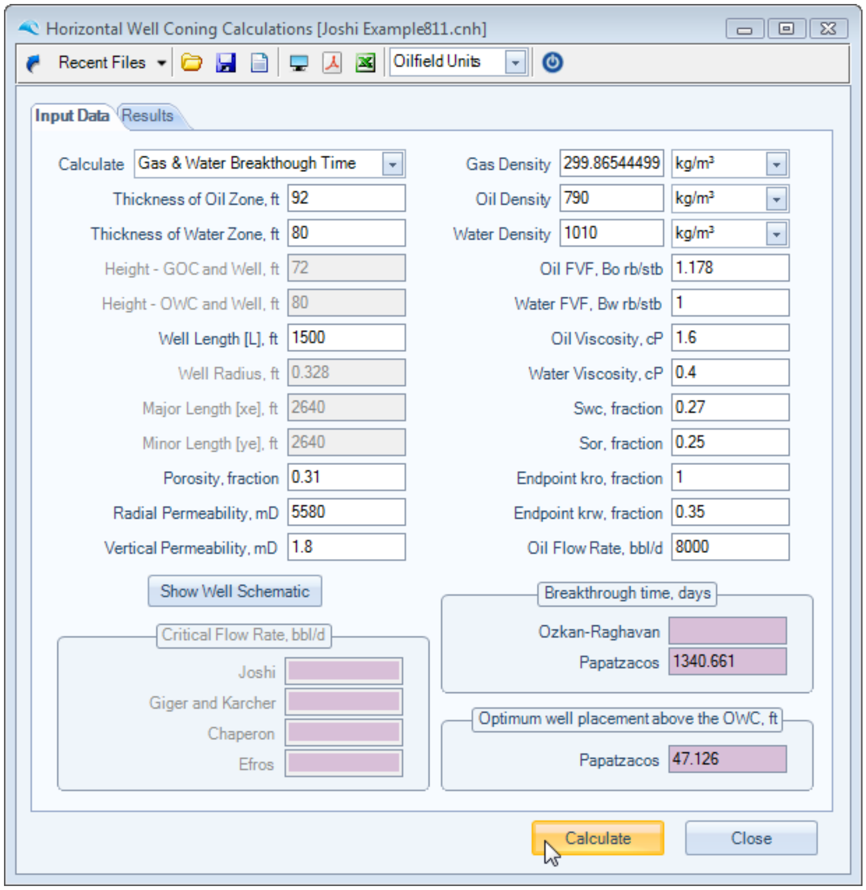
Thickness of Oil Zone, ft	160
Well Length [L], ft	2000
Well Radius, ft	0.328
Porosity, fraction	0.2
Radial Permeability, mD	200
Vertical Permeability, mD	20
Oil Density, gm/cc	0.76
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.1
Oil Viscosity, cP	1.3
Swc, fraction	0.27
Sor, fraction	0.25
Oil Flow Rate, bbl/d	5000



Gas and Water Breakthrough Time and Optimal Well Placement

From Joshi's Example 8.11, the following data is provided, and the Engineer is asked to calculate the breakthrough time and optimum well placement for simultaneous gas and oil breakthrough for a bottom water oil reservoir with a gas cap.

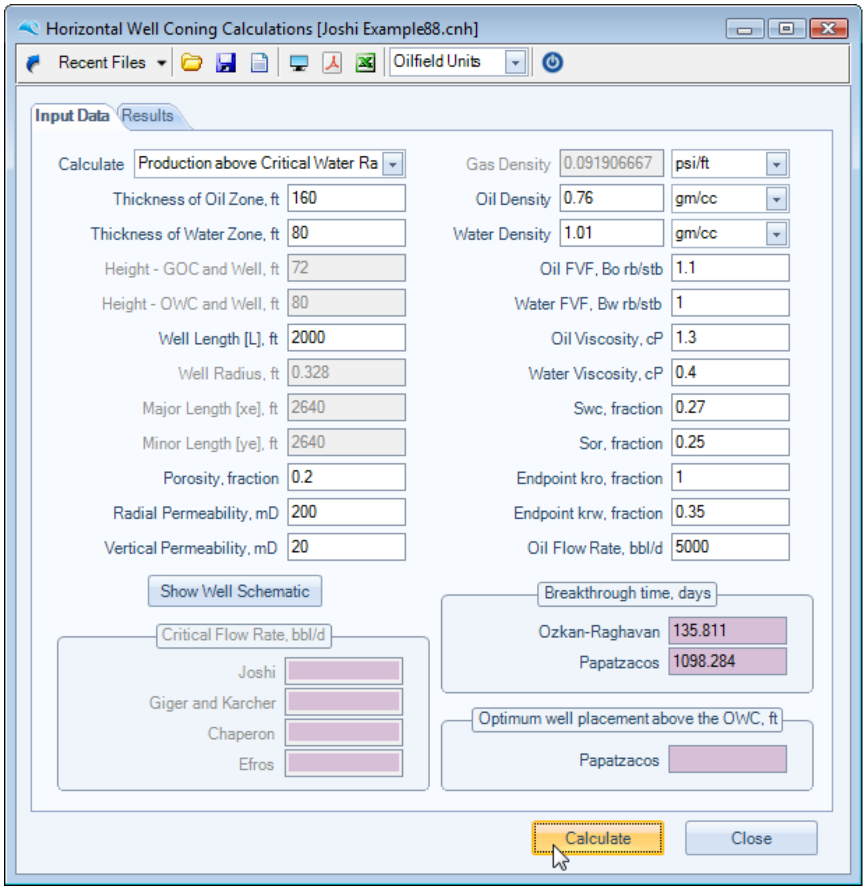
Input Data	
Thickness of Oil Zone, ft	92
Well Length [L], ft	1500
Well Radius, ft	0.328
Porosity, fraction	0.31
Radial Permeability, mD	5580
Vertical Permeability, mD	1.8
Gas Density, gm/cc	0.13
Oil Density, gm/cc	0.79
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.178
Oil Viscosity, cP	1.6
Oil Flow Rate, bbl/d	8000

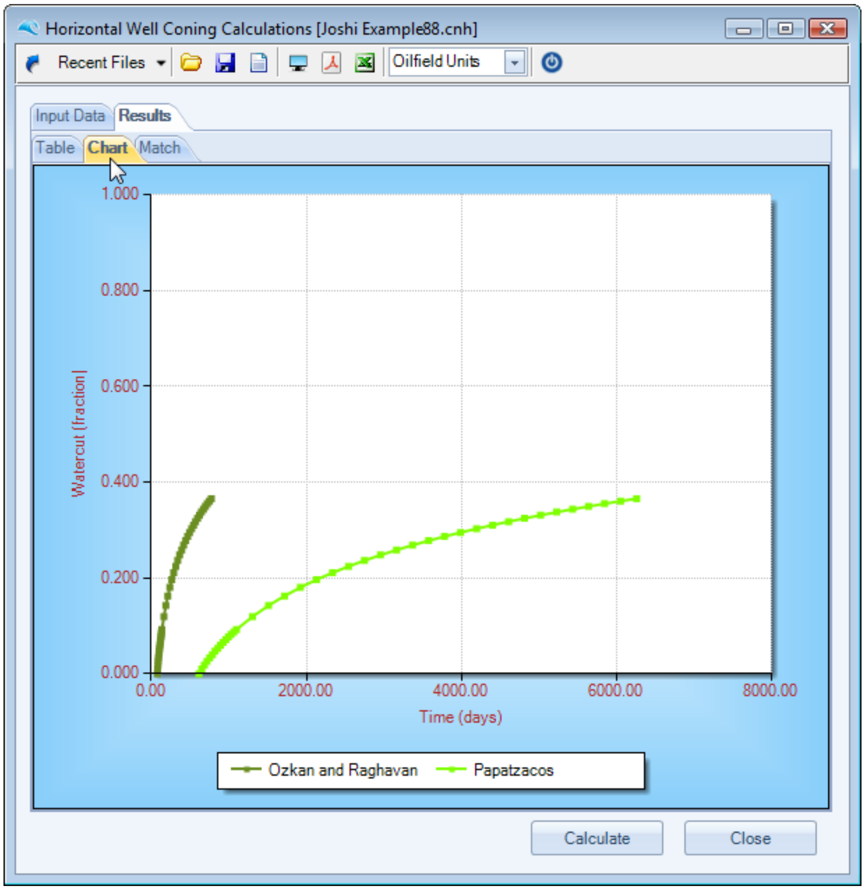


Production above Critical Water rate

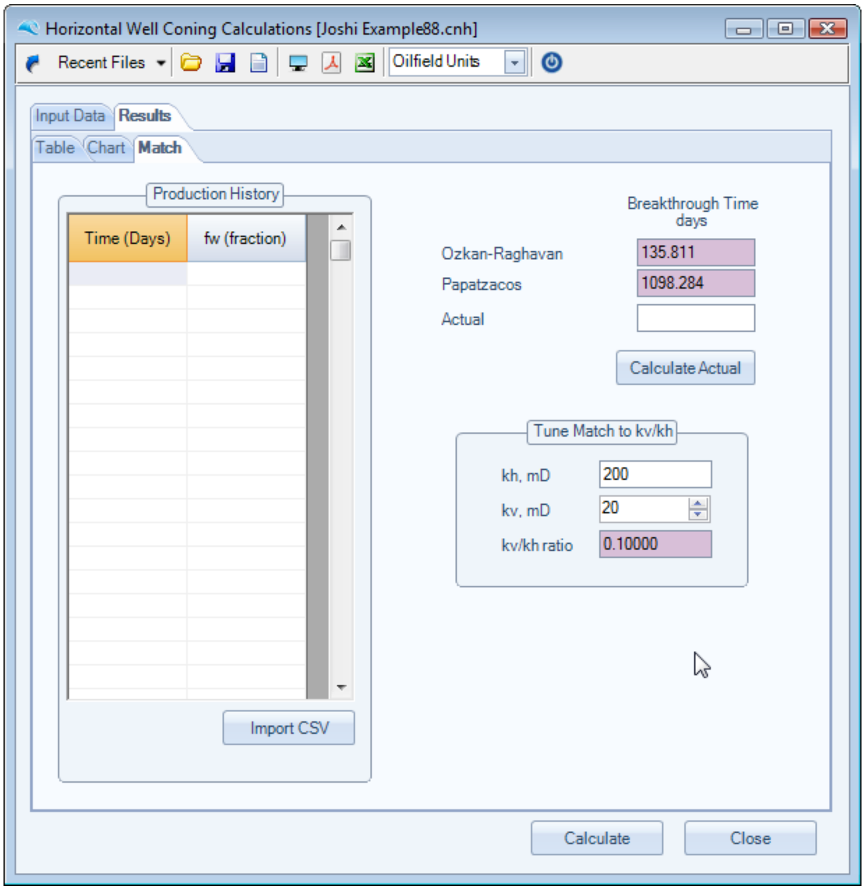
Extending Joshi's Example 8.8, the Engineer is asked to calculate the post water breakthrough performance for a bottom water oil reservoir, using the technique of Kuo and Desbrisay.

The following screenshots highlight the data input and resultant calculations

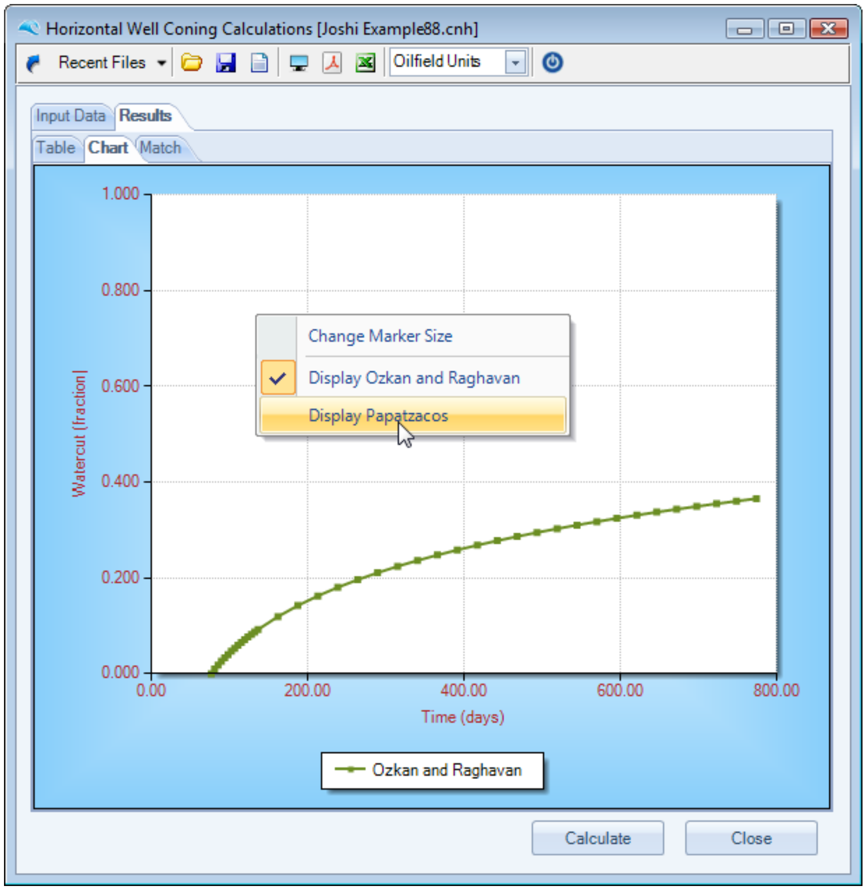

Horizontal Well Coning Calculations [Joshi Example88.cnh]
Recent Files
Oilfield Units
Input Data
Results
Calculate
Production above Critical Water Ra
Thickness of Oil Zone, ft
160
Thickness of Water Zone, ft
80
Height - GOC and Well, ft
72
Height - OWC and Well, ft
80
Well Length [L], ft
2000
Well Radius, ft
0.328
Major Length [xe], ft
2640
Minor Length [ye], ft
2640
Porosity, fraction
0.2
Radial Permeability, mD
200
Vertical Permeability, mD
20
Show Well Schematic
Critical Flow Rate, bbl/d
Joshi
Giger and Karcher
Chaperon
Efros
Gas Density
0.091906667
psi/ft
Oil Density
0.76
gm/cc
Water Density
1.01
gm/cc
Oil FVF, Bo rb/stb
1.1
Water FVF, Bw rb/stb
1
Oil Viscosity, cP
1.3
Water Viscosity, cP
0.4
Swc, fraction
0.27
Sor, fraction
0.25
Endpoint kro, fraction
1
Endpoint krw, fraction
0.35
Oil Flow Rate, bbl/d
5000
Breakthrough time, days
Ozkan-Raghavan
135.811
Papatzacos
1098.284
Optimum well placement above the OWC, ft
Papatzacos
Calculate
Close



Similar to the vertical well calculations, with the following input panel, and a knowledge of production history (time in days and watercut), the user can iterate vertical permeability to achieve an acceptable match.



To toggle on and off individual series within the chart, just toggle the chart context menu item, as shown below.

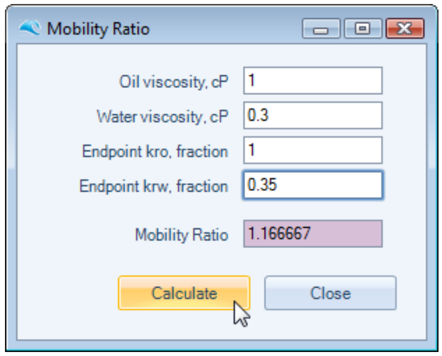

Horizontal Well Coning Calculations [Joshi Example88.cnh]
Recent Files
Oilfield Units
Input Data
Results
Table
Chart
Match
Change Marker Size
Display Ozkan and Raghavan
Display Papatzacos
Watercut (fraction)
1.000
0.800
0.600
0.400
0.200
0.000
0.00
200.00
400.00
600.00
800.00
Time (days)
Ozkan and Raghavan
Calculate
Close

Part VII

7 General Utilities

7.1 Mobility Ratio

A simple utility is provided to quickly calculate the waterdrive Mobility Ratio, and an example is included below.



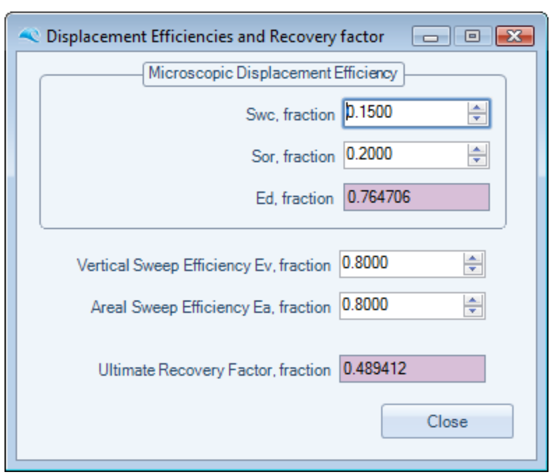
7.2 Displacement Efficiencies

The overall recovery efficiency of any fluid displacement process is given by the product of the macroscopic efficiency (or volumetric efficiency Ev x Ea - reservoir scale) and the microscopic displacement efficiency, Ed (pore scale).

A simple utility is provided to quickly iterate between initial connate water saturation (Swc), remaining or residual oil saturation (Sor) and vertical and areal sweep efficiencies to calculate ultimate recovery factor from the following.

Ultimate Recovery Factor = Ed * Ev * Ea, where Ed = (1-Sor-Swc) / (1-Swc).

An example is shown below.



7.3 Areal Sweep

Dyes et al. correlated the increase in areal sweep efficiency after breakthrough with the ratio of water volume injected at any time after breakthrough, W_{inj}, to water volume injected at breakthrough, W_{iBT}, as given by the following equation.

$$E_A = E_{ABT} + 0.633 \log\left(\frac{W_{inj}}{W_{iBT}}\right)$$

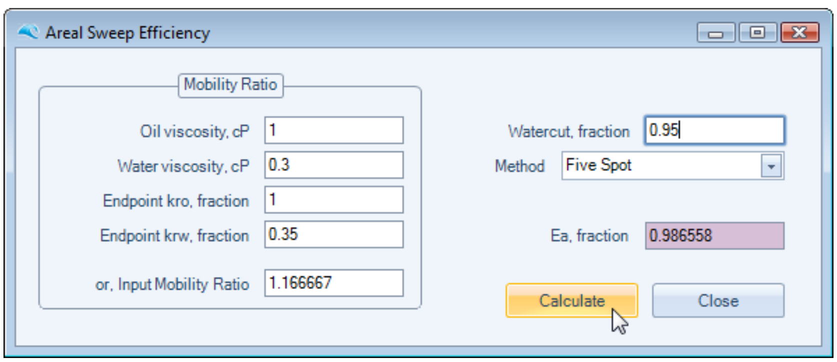
Dyes et al. also presented a graphical relationship that relates areal sweep efficiency with reservoir water cut fw and the reciprocal of mobility ratio 1/M.

Fassihi used a nonlinear regression model to reproduce these graphical relationships, by using the following expressions.

$$E_A = \frac{1}{1+A} \qquad \text{where,} \qquad A = (a_1 . \ln(M + a_2) + a_3) . f_w + a_4 . \ln(M + a_5) + a_6$$

Where coefficients a_1 to a_6 in the above equation depend on the waterdrive mechanism; ie., Five Spot, Direct Line Drive or Staggered Line Drive.

An example calculation is shown below.



References:

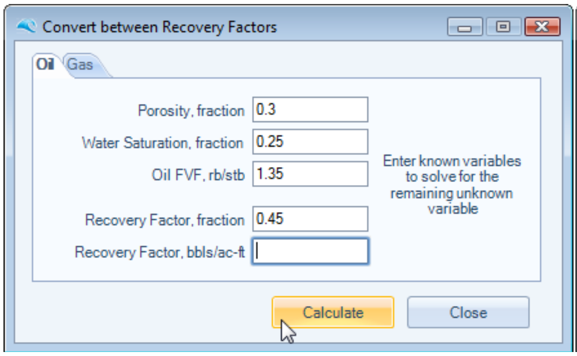
Dyes, A., Caudle, B., and Erickson, R., “Oil Production After Breakthrough as Influenced by Mobility Ratio,” *JPT,* April 1954

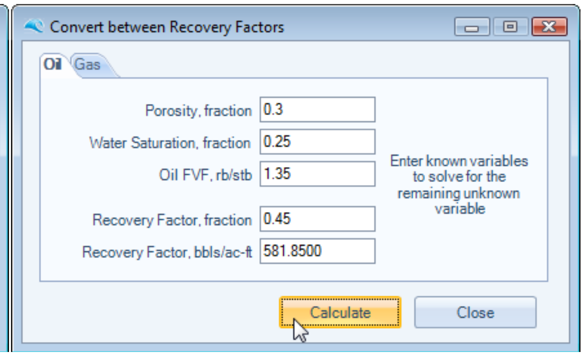
Fassihi, M., “New Correlations for Calculation of Vertical Coverage and Areal Sweep Efficiency,” *SPERE,* Nov. 1986

7.4 Convert Recovery Factors

A routine is provided to allow the user to quickly convert between commonly used variables for Recovery factor, namely recovery factor as a fraction, and as a barrel per acre-ft or for gas MMscf per acre-ft. The user can solve between any of the unknowns by simply leaving the required input cell empty.

An example calculation is shown below.

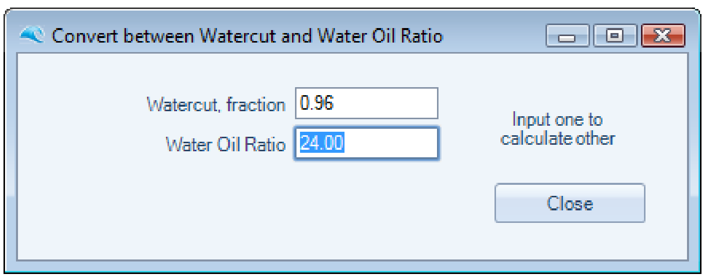




7.5 fw WOR Conversion

A simple utility is provided to quickly convert between Watercut and Water-Oil Ratio.

An example is shown below.

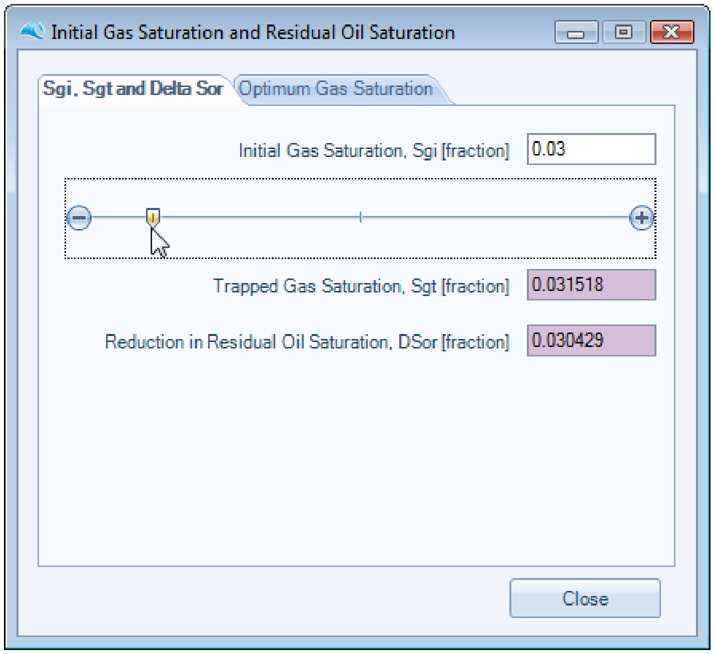


7.6 Trapped Gas Saturation and Residual Oil Saturation

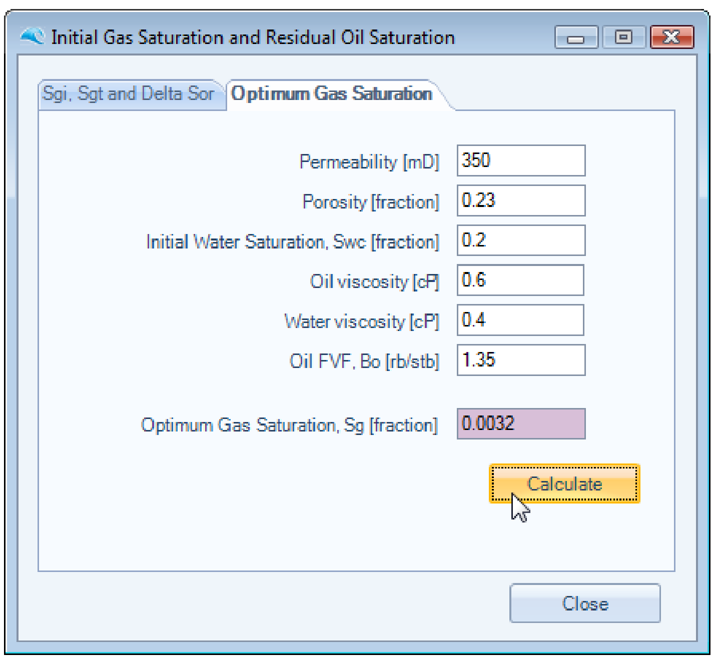
Craig published two correlations to account for the reduction in residual oil saturation as a result of the presence of initial gas saturation.

The first correlation linked initial gas saturation, Sgi, to trapped gas saturation, Sgt.

The second correlation linked trapped gas saturation, Sgt, to the reduction in residual oil saturation, Δ Sor. These correlations are included within the first datatab and an example calculation is shown below :



Khelil suggests that waterflood recovery can possibly be improved if a so-called “optimum gas saturation” is present at the start of the flood. This correlation is included within the second datatab and an example calculation is shown below :



References:

Cole, F., *"Reservoir Engineering Manual"*, Gulf Publishing Company, 1969

Craig, Jr., F., *"The Reservoir Engineering Aspects of Waterflooding"*,Society of Petroleum Engineers, 1971

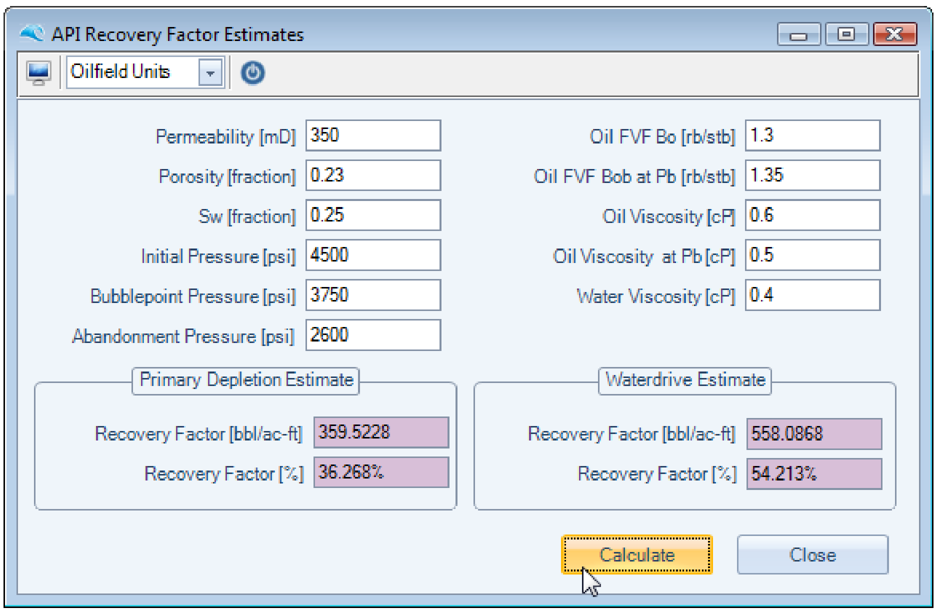
Khelil, C., "*A Correlation of Optimum Free Gas Saturation With Rock and Fluid Properties*", SPE Paper 1983, 1967

Ahmed, T., "*Reservoir Engineering Handbook*", Elsevier, 2006

7.7 Recovery Factors

The API Subcommittee on Recovery Efficiency presented a statistical study of recovery efficiency in 1967. From a statistical analysis of data from 312 reservoirs, they developed correlations for water drive recovery from sandstone reservoirs, and for solution gas drive recoveries from sandstone and carbonate reservoirs.

Their correlations have been implemented within this utility and an example calculation is shown below :



References:

Arps., J. J., Brons, F., van Everdingen, A. F., Buchwald, R. W. and Smith, A. E.: "*A Statistical Study of Recovery Efficiency*" Bulletin 140, API, 1967

7.8 Fit Corey Curves

An often used approximation of relative permeability is the Corey correlation which is a power law relationship with respect to water saturation.

These equations are highlighted for completeness below.

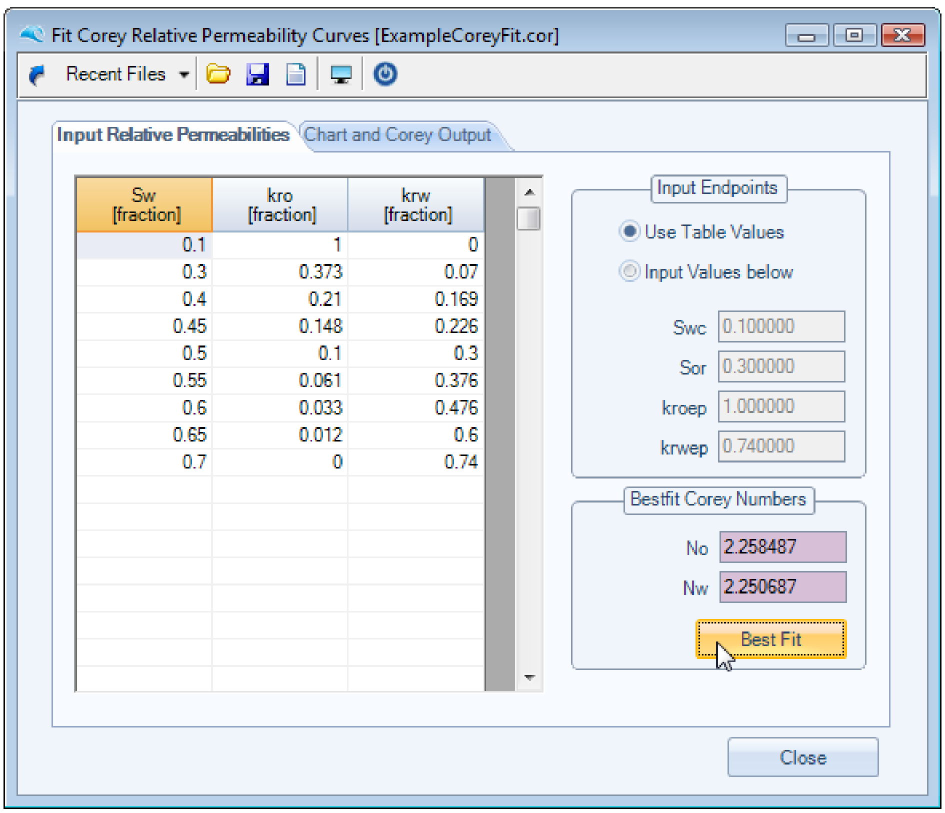
$$k_{ro} = k_{roep} \times \left[\frac{1 - S_w - S_{or}}{1 - S_{wc} - S_{or}}\right]^{N_o}$$

$$k_{rw} = k_{rwep} \times \left[\frac{S_w - S_{wc}}{1 - S_{wc} - S_{or}}\right]^{N_w}$$

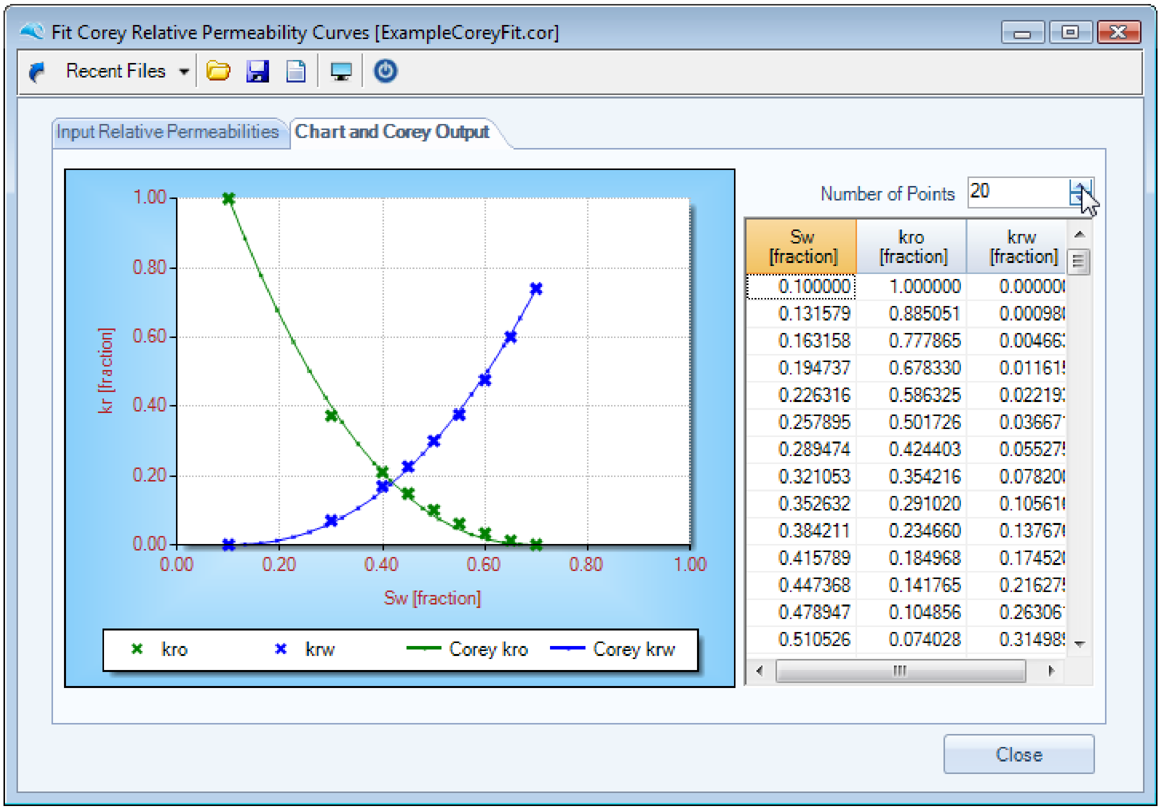
A simple utility to curve fit Corey type curves for a relative permeability dataset.

Simply type the relative permeability numbers (or more conveniently copy [CTRL+C] and paste [CTRL+V], or drag and drop) into the **Input Relative Permeability** datatab, choose to input user endpoints or use the table values, then press the **Best Fit** button, as shown below.

The bestfit exponents of the Corey Relative Permeability equations will then be calculated.



The user can view the relative permeability data and fit in the chart provided, and can also choose to copy and paste the calculated Corey Relative Permeability data for use within other routines in this or other applications. To copy data from the datatab shown below, simply highlight and drag your selection within the table and press CTRL+C to copy to the clipboard.



References:

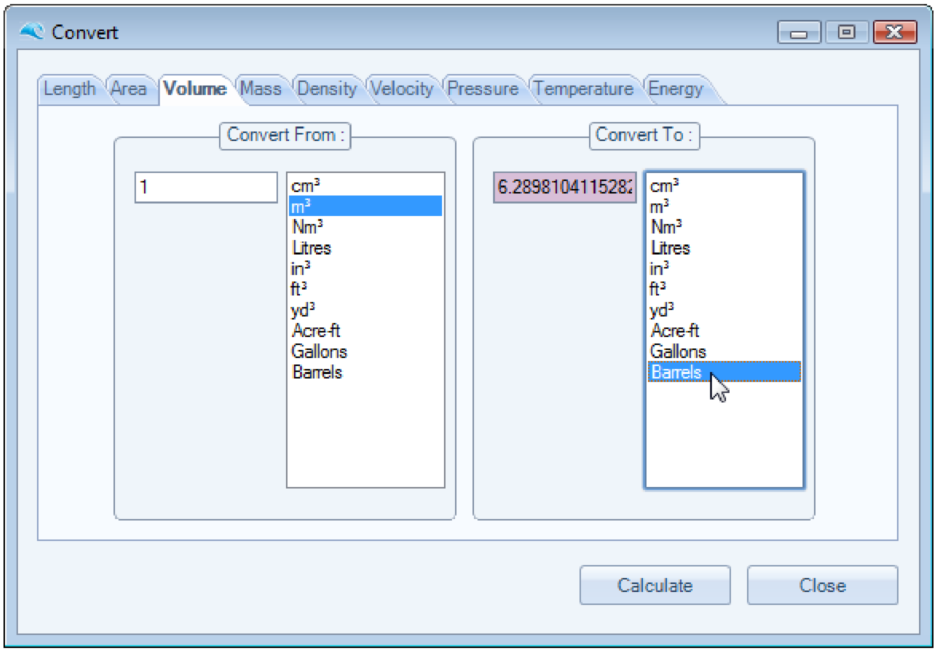
Corey, A.T. "The Interrelation Between Gas and Oil Relative Permeabilities". Production Monthly, Nov 1954

7.9 Units Conversion

Most commonly used oil industry conversion factors have been implemented into this general purpose units conversion application.

Just type a number in the **Convert From** input box, select a unit, then double click on the **Convert To** unit, and the result will appear in the highlighted Convert To result box.

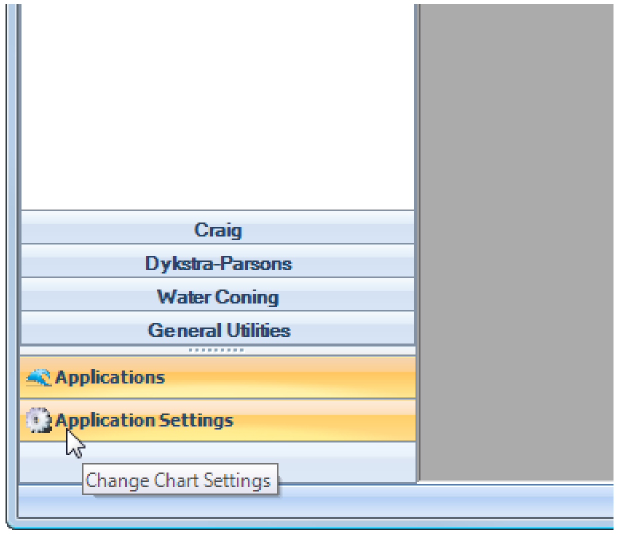
An example is shown below.


Convert
Length
Area
Volume
Mass
Density
Velocity
Pressure
Temperature
Energy
Convert From :
1
cm³
m³
Nm³
Litres
in³
ft³
yd³
Acre-ft
Gallons
Barrels
Convert To :
6.289810411528
cm³
m³
Nm³
Litres
in³
ft³
yd³
Acre-ft
Gallons
Barrels
Calculate
Close

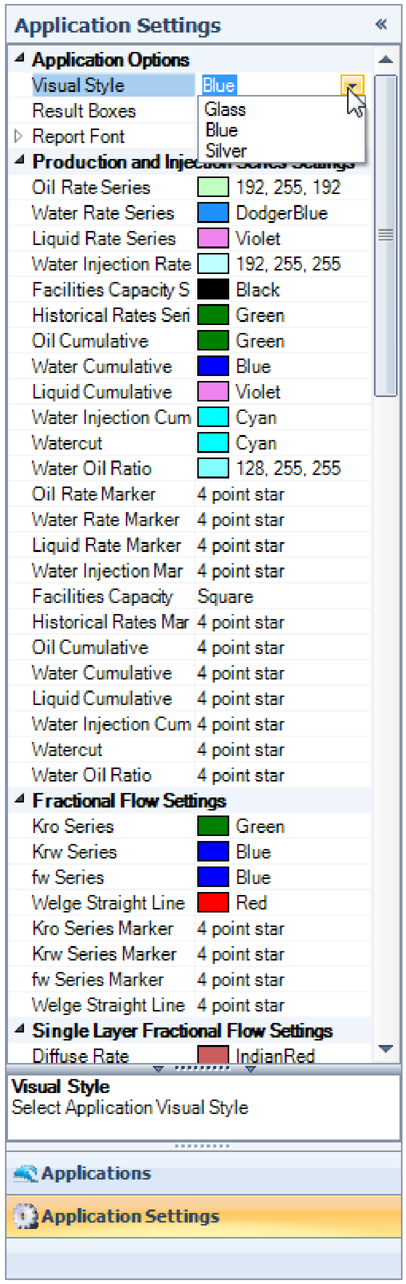
Part VIII

8 Application and Chart Settings

To change aspects of the application or chart settings, select the Application Settings toolbar located at the bottom right of the main application window, as shown below.



Once this toolbar is selected the contents of the toolbar area should change to a editable property grid and allow the User to change most aspects of the application and chart preferences.



The User can scroll up and down within this property grid and modify the application and chart settings to suit their requirements.

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