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Testing of the IGARF1 v4 spreadsheet tool for assessing the impacts of groundwater abstraction on river flows

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Testing of the IGARF1 v4 spreadsheet tool for assessing the impacts of groundwater abstraction on river flows

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IGARF; groundwater abstraction; river flows.

Bibliographical reference

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Summary

This report describes the testing of the IGARF1 v4 spreadsheet tool, developed by the Environment Agency, for the assessment of the impacts of groundwater abstraction on river flows. This spreadsheet, constructed in Microsoft Excel, calculates the effect that a constant or periodic groundwater abstraction has on a groundwater system containing one or two straight-line rivers. The testing involves the simulation of a number of different aquifer configurations to examine if and when the tool has difficulty in calculating a solution. In addition to examining the robustness of the spreadsheet, a number of comparisons are made with a numerical model. There is close agreement between the results produced by the numerical model and the IGARF tool in these comparisons.

Whilst the testing has shown that the spreadsheet is a Powerful and easy to use modelling application, that generally produces accurate results rapidly, a number of problems have been encountered. One problem appears to relate to the execution of the dynamic link library (dll) and it is suspected that an error in the dll can cause the tool to crash. This has occurred approximately 6 times during this investigation and appears to be due to memory referencing or allocation errors. However, it is not absolutely certain that the error lies within the dll and it could be a problem with the code contained in an Excel macro. This problem should be resolved before the tool is released to organisations external to the Environment Agency.

Four models have been constructed using both the IGARF1 v4 spreadsheet and a numerical model and a comparison has been made between the results of each. The results are in close agreement, except in one example where, as expected, the river becomes perched due to abstraction.

The use and testing of the spreadsheet has illustrated that in most cases it returns accurate results. In general it is straightforward to obtain the correct results, however, in approximately half of the model runs, the Scale Factor and Power parameters, on the *rdf functions* sheet, had to be adjusted to resolve the warning messages that are presented after the solution is calculated.

In most cases the warning messages can be resolved quickly, generally by adjusting the *Scale Factor* parameter only. However, for some models it was not possible to resolve the warning messages by adjusting either or both of the Scale Factor and Power parameters. This problem occurred in examples with realistic parameters and did not just occur in aquifers with unrealistic data sets as expected.

Whilst numerical warning messages are presented frequently after the calculation of a solution by the IGARF1 v4 spreadsheet, the appropriate warnings were always found to appear at the correct time when they were required to direct the user.

1 Introduction

The Environment Agency's IGARF1 v4 tool is a spreadsheet based modelling application, created in Microsoft Excel, that enables the investigation of the impact of groundwater abstraction on river flows in a system containing either one or two straight-line rivers. The tool uses three different analytical solutions to assess the impacts in a vide variety of simplified surface-groundwater systems. The analytical solutions are those presented by:

1. Theis (1941)

   Analytical solution to calculate the quantity of water supplied from a fully penetrating infinite river, or infinite straight-line recharge boundary, due to a constant rate groundwater abstraction.

2. Hantush (1965)

   Analytical solution to an infinite straight-line, fully penetrating river considering the influence of low hydraulic conductivity river bank or river bed sediments

3. Hunt (1999)

   Analytical solution to an infinite straight-line, partially penetrating river considering the influence of low hydraulic conductivity river bed sediments

This work describes the testing that has been undertaken on the latest version (version 4) of the IGARF1 Excel spreadsheet. The following tasks have been undertaken as part of the five-person days of testing and this report is broken down into sections, which approximately relate to each of these tasks.

1. Undertake the spreadsheet modelling described in the case study in Section 5 of the IGARF1 v4 User Manual (Environment Agency, 2004)
2. Try to find bugs in the program by simulating aquifer systems with extreme parameter values. Identify aquifer configurations for which the tool has difficulty in producing a correct solution e.g. steep groundwater head gradients, very concentrated / diffuse river impacts
3. Compare IGARF results with simple numerical models to check accuracy, considering that IGARF can assess heads at all points in model space and, therefore, the numerical model may require a very fine mesh.
4. Assess how often the numerical accuracy issues arise, in cases:
   - Using realistic datasets (different to the case study in Section 5 of the User Manual).
   - With extreme parameters / in unrealistic situations.
5. When numerical issues do occur, assess how easy they are to correct.
6. Check that the appropriate numerical warning messages are shown at the appropriate times.

All the spreadsheet modelling referred to in this work has been performed on a Pentium III PC with 512 Mb of RAM running Windows 2000 and Microsoft Excel 2000.

2 User Manual case study of the River Otter

The case study described in Section 5 of the User Manual for IGARF1 v4 (Environment Agency, 2004) has been replicated using both versions of the Excel spreadsheet i.e. IGARF1v4.xls and IGARF1v4 no report.xls. The "no report" version is for use on portable lap top machines and does not incorporate the facility to produce short reports, or modelling logs, which are printed using the Environment Agency's computing network. This case study illustrates its application to the assessment of the impact of an abstraction close to the River Otter in Devon flowing across the Permo-Triassic sandstone. The steps described in the User Manual have been replicated using both versions of the Excel file. No differences have been found when comparing simulated results with those presented in the User Manual.

3 Bugs & error hunting

3.1 BUG 1

This was encountered when using the version of the spreadsheet containing the reporting facility. Whilst following the River Otter case study and examining the time-drawdown curves discussed in Section 5.2.7 of the User Manual the following error occurred:

- After having previously followed the example to the end of Section 5.2.7 successfully, the x-axis maximum of the time-drawdown curve was changed a few times. It was then changed back to 180 days and the *Calculate Now* button was pressed again. It then appeared that the code (possibly contained in the dll) could not reference the required area of memory. A Windows pop-up error message was presented specifying this error, which gave the option to debug. On pressing OK (to skip debugging) Excel was shut down.

A number of attempts were made to repeat this error by following the same steps but the problem did not recur.

The same problem was encountered on pressing *Calculate Now* after having filled in the *Data Sheet* to run the Example C.7 in Appendix C of the User Manual (Figure 1). This problem was not encountered when a second attempt was made to run the model. However, this error did recur approximately five times, generally when the *Calculate Now* button was pressed.

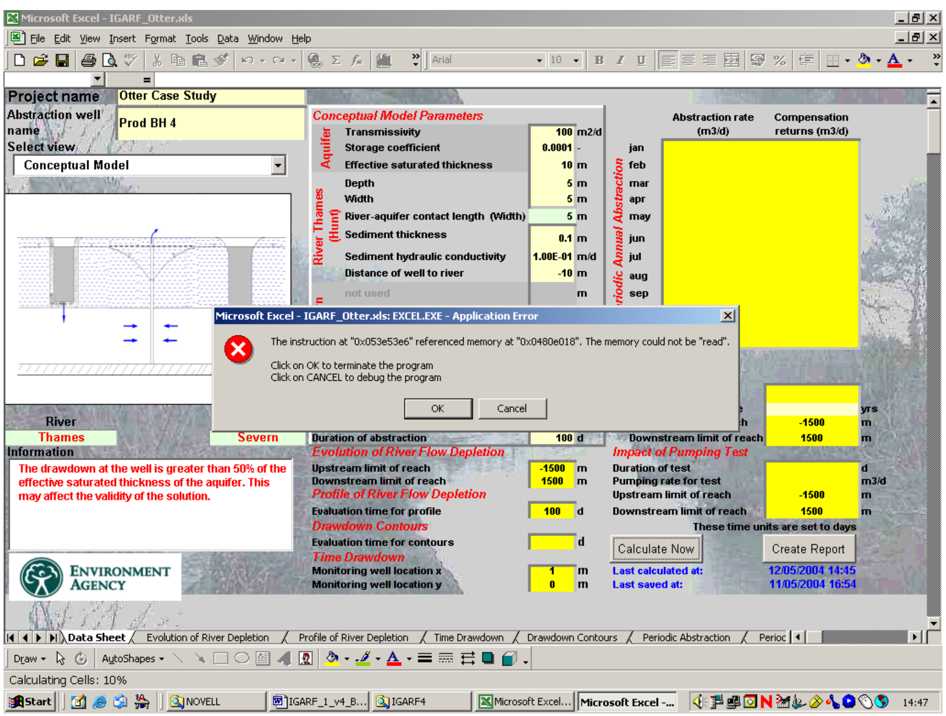

Figure 1 Error during running of Example C.7 in Appendix C.

3.2 BUG 2

This was encountered when using the version of the spreadsheet containing the reporting facility. After having reached the end of Section 5.2.4 of the User Manual the following steps were performed:

- The contents of the cell containing the *Downstream limit of reach evaluated* were copied and pasted into the cell above, containing the upstream limit.
- The *Upstream limit of reach evaluated* was then adjusted to be –1000 instead of –1500. This resulted in the error message below. Which could only be corrected by modifying its value in the *Data Sheet*. See Figure 2.
- This error message was not presented if values greater than 1500 were then input as the upstream reach limit.

This may not be viewed as a bug but rather as the problems associated with the use of *Copy*➔*Paste* instead of the use of *Copy*➔*Paste Special*➔*Values*.

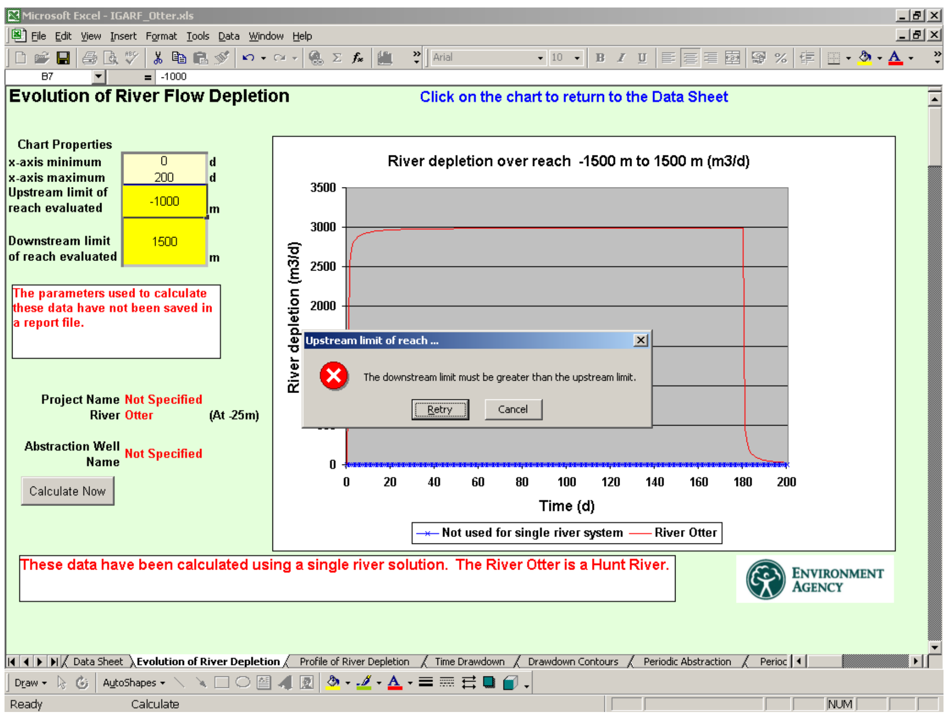

Figure 2 Screen dump showing bug 2

3.3 BUG 3

The drop down box on the *Periodic Abstraction* sheet is not *protected* and can be deleted.

4 Comparison with numerical model

4.1 BACKGROUND

Four comparisons have been made between the results produced by the IGARF spreadsheet with those produced by the finite-difference numerical groundwater flow model ZOOMQ3D (Jackson, 2001). Except for comparison four, the numerical models contain a uniform square mesh spacing that is smaller or comparable to the distances between the simulated abstraction boreholes and rivers. Consequently the numerical models are considered to contain sufficient resolution. The numerical models used in comparison 1 to 3 are not presented as figures because they use simple uniform dense meshes, which are clear to envisage.

Comparisons are been made between IGARF and ZOOMQ3D for the time-drawdown curves, the evolution or river depletion curves, and the profiles of river depletion, for models using both constant and periodic abstraction rates. Table 1 gives a summary of the models described in the following four sections.

Table 1 Summary of the comparative models

Comparison	Description
1	Pumped well equidistant from two Hunt type rivers that are 4 km apart. Hydraulic parameters are broadly representative of a Chalk aquifer i.e. a transmissivity of 1000 m^2day^{-1} and storage coefficient of 1%. Abstraction borehole pumps at a constant rate of 10,000 m^3day^{-1} for 200 days. Comparative plots are produced for the time-drawdown at an observation borehole, for the evolution of river depletion, and for the profile of river depletion.
2	The model is the same as that constructed in Comparison 1 except it includes periodic abstraction. The well pumps for half of each year, between May and October, at a rate of 10,000 m^3day^{-1}. A comparative plot is produced for the evolution of river depletion over time.
3	A model is constructed to illustrate the impact of river becoming perched on the model solution. An abstraction borehole is located 125 m from a Hunt type river in an aquifer with a transmissivity of 200 m^2day^{-1} and storage coefficient of 5%. Comparative plots are produced for the time-drawdown at an observation borehole, for the evolution of river depletion, and for the profile of river depletion.
4	The example described in Appendix C.4 of the IGARF1 v4 User Manual, in which an abstraction borehole is pumped at a rate of 1000 $m^3\ day^{-1}$, and which is 10 m from a Theis type river and 100 m from a Hunt type river, is reproduced. A comparative plot is produced for the profile of river depletion after 100 days of pumping.

4.2 COMPARISON 1

In this comparison a pumped well is located midway between two Hunt type rivers, which are 4 km apart. The hydraulic parameters assigned to the model are broadly representative of a Chalk aquifer i.e. a relatively high transmissivity of 1000 $m^2\ day^{-1}$ and a relatively low storage coefficient of 1% are applied. The abstraction borehole pumps at a constant rate of 10,000 m^3day^{-1} for 200 days. The full parameter data set is illustrated in Figure 3, which shows the *Data Sheet* for the IGARF model.

The numerical model is 20 km square and has a 125 m square mesh. The abstraction borehole is located in the centre of the model. The rivers are 2 km from the pumped well and are assigned the same parameters as those input to the IGARF spreadsheet. A one-day time-step is used to simulate the system.

Three charts are produced (Figures 4 to 6) which show the comparison between the analytical and numerical model for:

- the time-drawdown at an observation well halfway between the well and one of the rivers (with time shown on a log scale),
- the evolution of river depletion over the reach 2 km upstream to 2 km downstream of the well (with time shown on a log scale) and,
- the profile of river depletion along the central 20 km one of the rivers after 200 days of pumping.

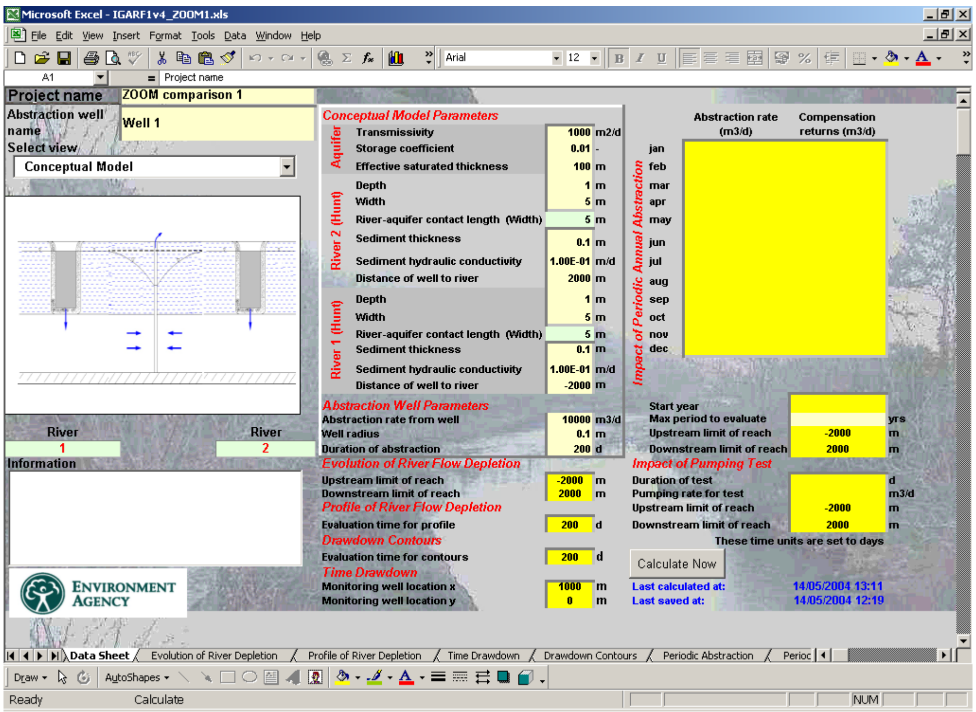

Figure 3 Data Sheet of IGARF model used for ZOOMQ3D comparison 1

Figures 4 to 6 show that there is close agreement between the analytical and numerical model solutions for each of the three types of impact plotted for this first comparison. Figure 4 and 5 show the s-shaped nature of the time-drawdown and evolution of river depletion curves, when plotted on a log-time axis, with the system approaching steady-state after approximately 100 days. The time-drawdown and evolution of river depletion curves are very similar but small differences are apparent at early times i.e. less than 5 days after the start of pumping. This is due to the numerical model being less accurate at the start of the simulation due to the use of a relatively coarse one-day time-step. Figure 6 shows the profiles of river depletion after 200 days and obviously illustrates that the greatest impact on the river is closest to the well. The two profiles of river depletion are also in very close agreement and there are no visually discernible differences between the two model plots.

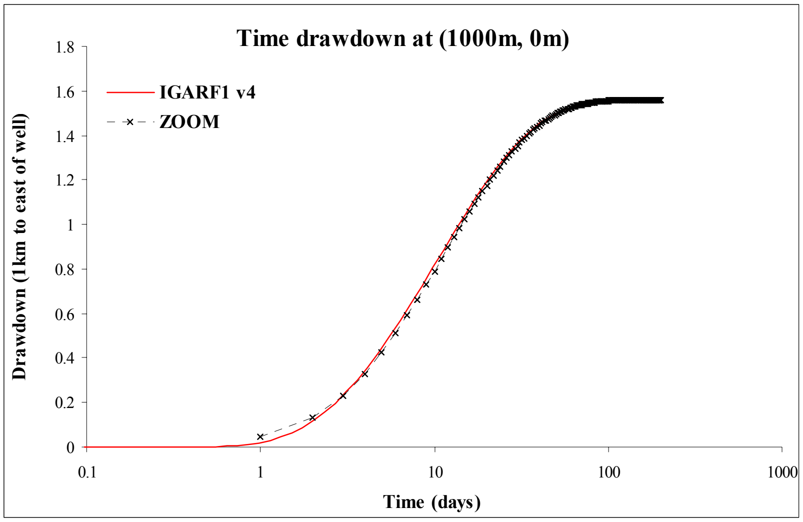

Figure 4 Time-drawdowns curves for ZOOMQ3D comparison 1

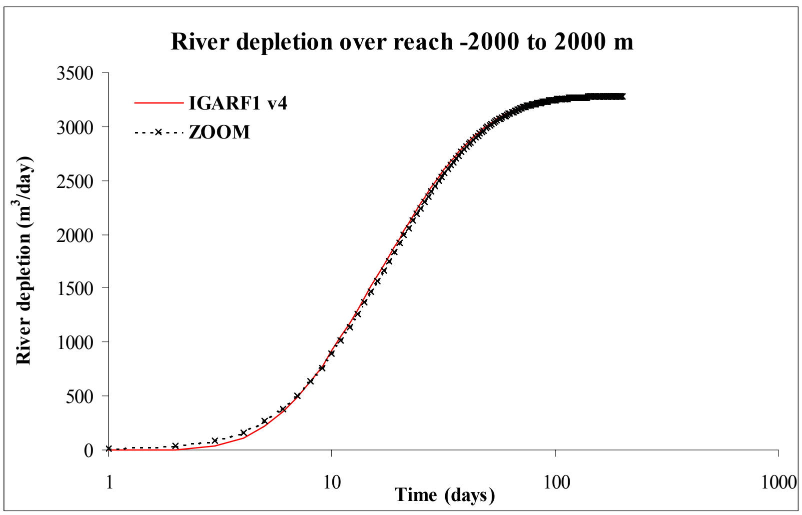

Figure 5 Evolution of river depletion curves for ZOOMQ3D comparison 1

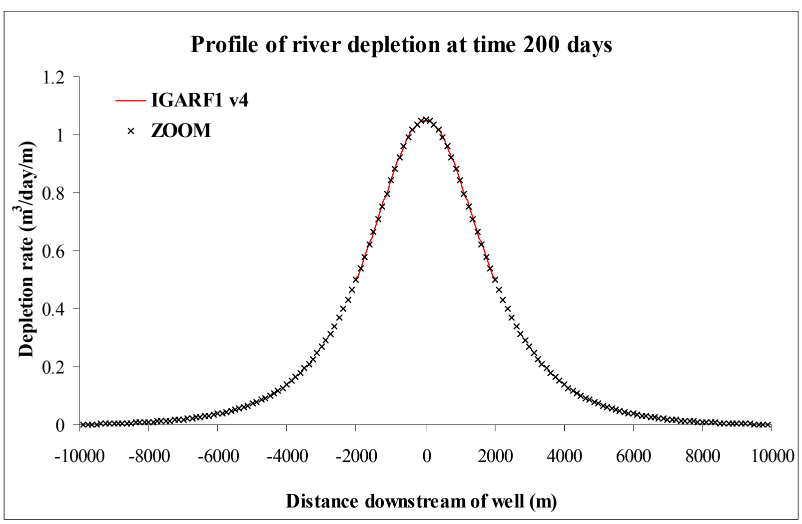

Figure 6 Profile of river depletion for ZOOMQ3D comparison 1

4.3 COMPARISON 2

This comparison uses the same model as that used for comparison 1. However, in this simulation the abstraction borehole pumps periodically. The well pumps for six months between May and October at a rate of 10,000 m^3day^{-1}. The full parameter data set is illustrated in Figure 7, which shows the *Data Sheet* for the IGARF model.

The numerical model is the same as that used in comparison 1 except that the periodic abstraction is included and the time-step is modified. In this mode there are 11 time-steps per month which increase in length from one day at the start of the month.

A single chart is produced (Figure 8) which shows the comparison between the analytical and numerical model for:

- the evolution of river depletion over the reach 2 km upstream to 2 km downstream of the well.

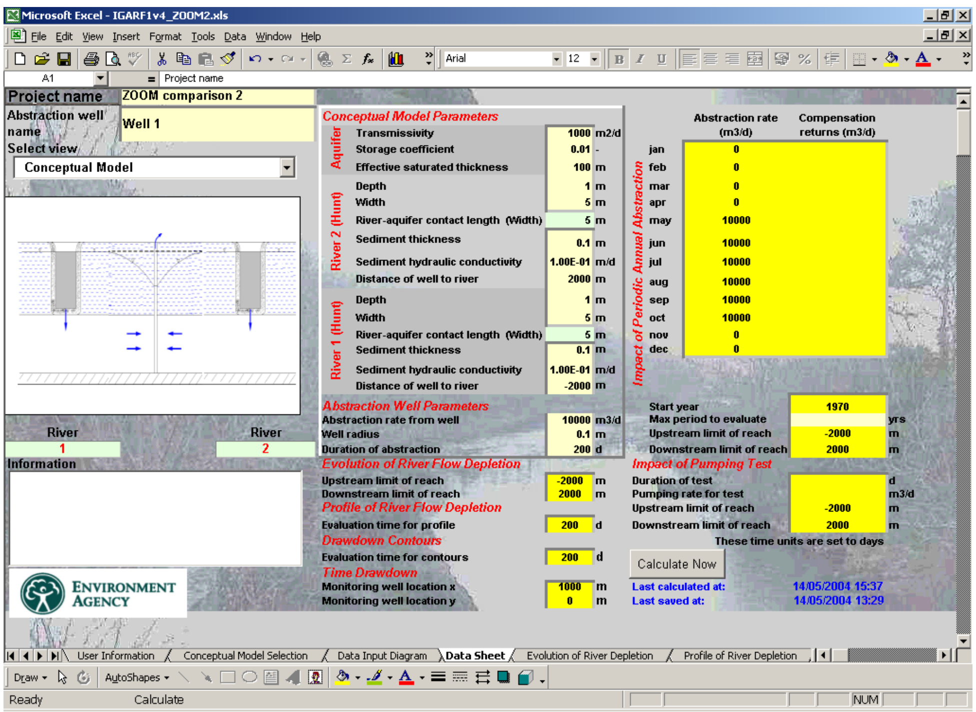

Figure 7 Data Sheet of IGARF model used for ZOOMQ3D comparison 2

The comparison between the two models for the evolution of river depletion is shown in Figure 8. This again shows that the two models are in good agreement. In particular the rising and falling limbs of the curve are in close agreement. However, the numerical model does simulate slightly greater depletion rates towards the end of the six-month period of abstraction. The exact reason for this has not been identified due to time constraints but the difference is not sufficiently significant to draw the conclusion that there are errors in either of the models.

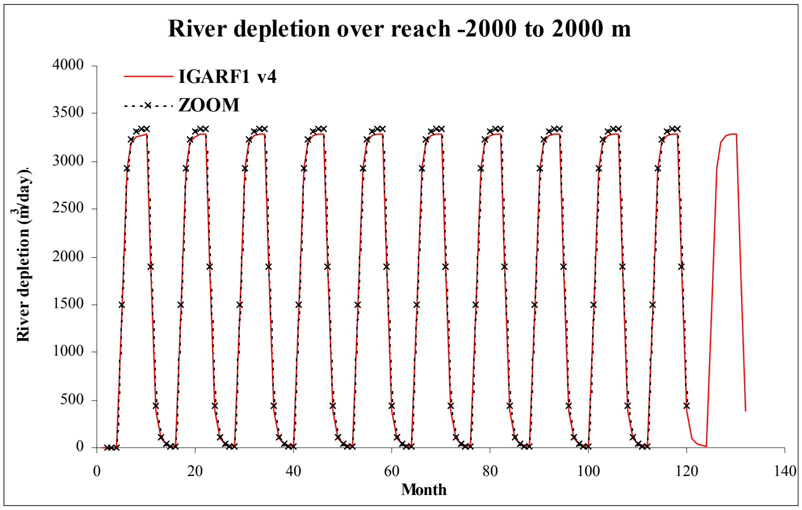

Figure 8 Evolution of river depletion curves for ZOOMQ3D comparison 2

4.4 COMPARISON 3

In this comparison a model is constructed to illustrate the impact of perching of the rivers on the solution. An abstraction borehole is located 125 m from a Hunt type river in an aquifer with a transmissivity of 200 m^2day^{-1} and storage coefficient of 5%. The full parameter data set is illustrated in Figure 9, which shows the *Data Sheet* for the IGARF model.

The numerical model is 20 km square and has a 125 m square mesh. The river is 125 m from the pumped well and is assigned the same parameters as those input to the IGARF spreadsheet. A one-day time-step is used to simulate the system.

Three charts are produced (Figures 10 to 12) which show the comparison between the analytical and numerical model for:

- the time-drawdown at an observation well located on the river,
- the evolution of river depletion over the reach 1 km upstream to 1 km downstream of the well and,
- the profile of river depletion along the central 4 km of one of the rivers after 200 days of pumping.

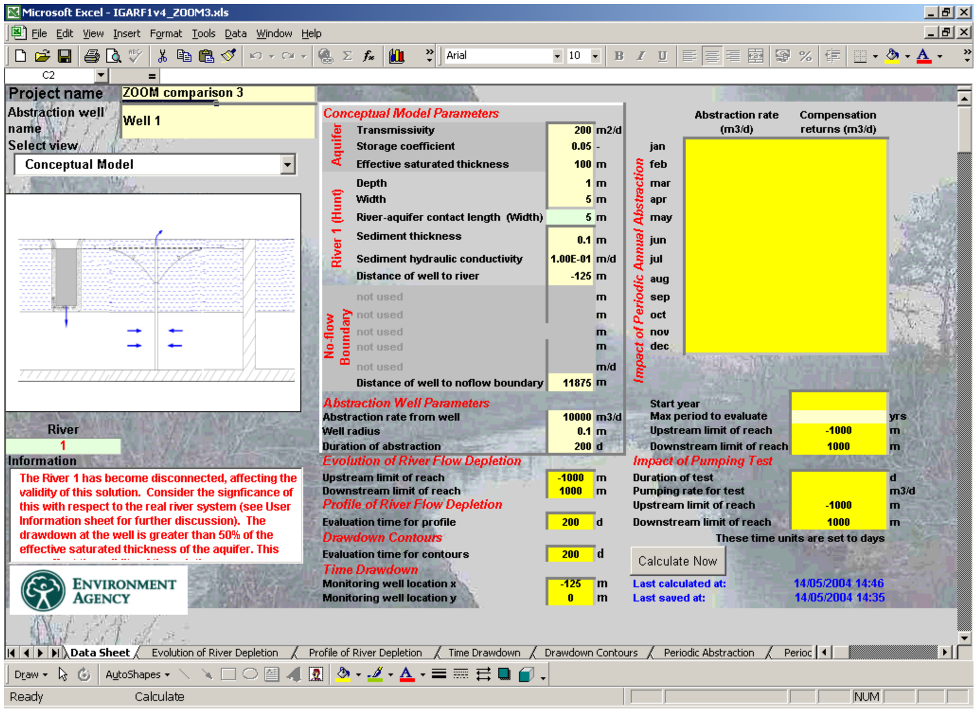

Figure 9 Data Sheet of IGARF model used for ZOOMQ3D comparison 3

The impact of the river becoming perched, i.e. when the groundwater head falls below the bed of the river, is clearly visible in all three comparative plots shown in Figures 10 to 12. The numerical model predicts that the river becomes perched over an 875 m length of channel (equivalent to seven model river nodes) by the end of the 200-day period of abstraction, (represented by seven central points on curve in Figure 10). However, the section of the river closet to the abstraction well becomes perched after only two-days of pumping in the numerical model. This perching has a significant impact on the subsequent drawdown and depletion rates.

At early times after the start of pumping the time-drawdown curves for the two models are in relatively close agreement. However, after approximately 25 days of abstraction the curves diverge. Rates of drawdown are more rapid in the numerical model because perching of the river limits the supply of water to the well close to the borehole. This is observed in the evolution of river depletion rates (Figure 12) which illustrates the lower river leakage rates to the aquifer in the numerical model.

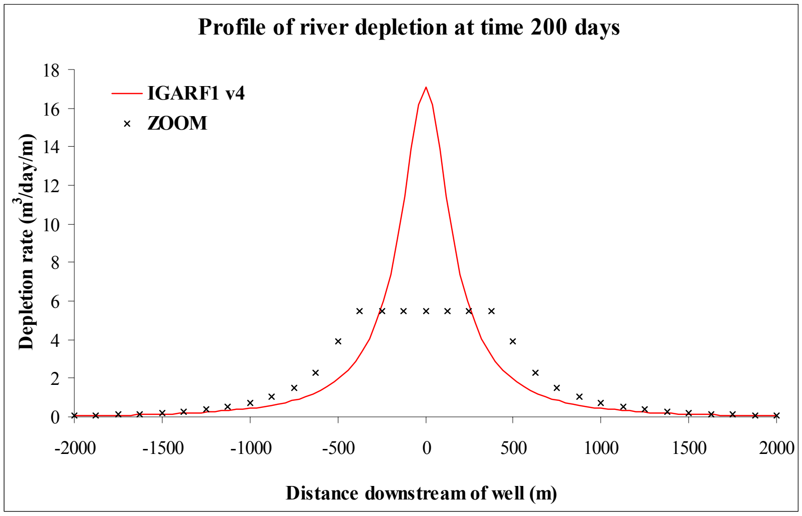

Figure 10 Profiles of river depletion for ZOOMQ3D comparison 3

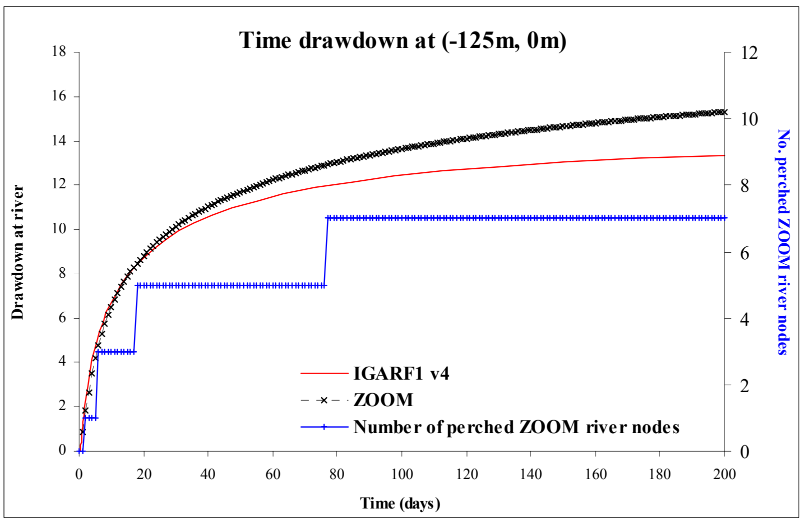

Figure 11 Time-drawdown curves for ZOOMQ3D comparison 3

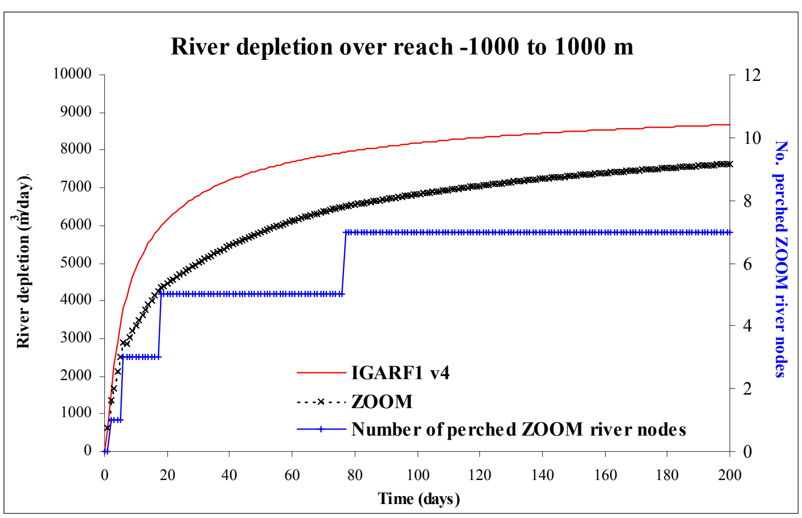

Figure 12 Evolution of river depletion curves for ZOOMQ3D comparison 3

4.5 COMPARISON 4

In this comparison a numerical model is constructed which represents the example described in Appendix C.4 of the IGARF1 v4 User Manual. In this scenario an abstraction borehole is pumped at a rate of 1000 m^3day^{-1}, which is 10 m from a Theis type river and 100 m from a Hunt type river. The full parameter data set is illustrated in Figure 13, which shows the *Data Sheet* for the IGARF model.

The numerical model is shown in Figure 14. The model is 4 km square and in the area of interest, around the well and rivers, the mesh spacing is 10 m square.

As discussed in Appendix C of the User Manual the spreadsheet cannot calculate the evolution of river depletion for this scenario but can calculate the profile of river depletion after 100 days of pumping. Consequently, in this comparison only one comparative plot is produced, which is the profile of river depletion after 100 days of pumping. This illustrates that in this relatively low transmissivity and low storage, shallow aquifer in which the pumped well is close to two rivers, there is close agreement between the two models (Figure 15).

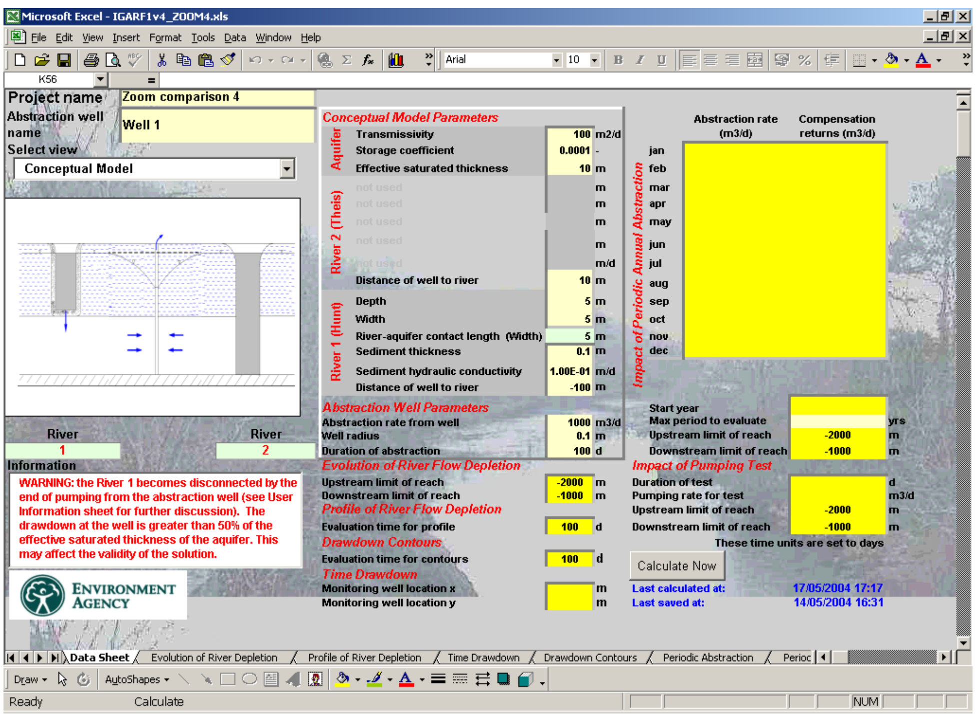

Figure 13 Data Sheet of IGARF model used for ZOOMQ3D comparison 4

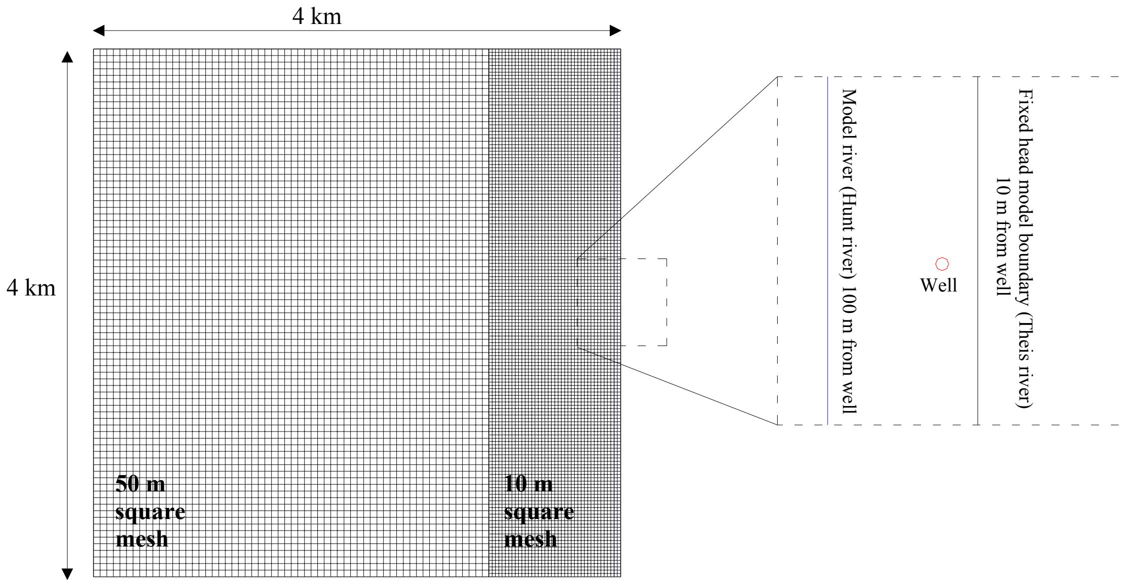

Figure 14 ZOOMQ3D model for comparison 4

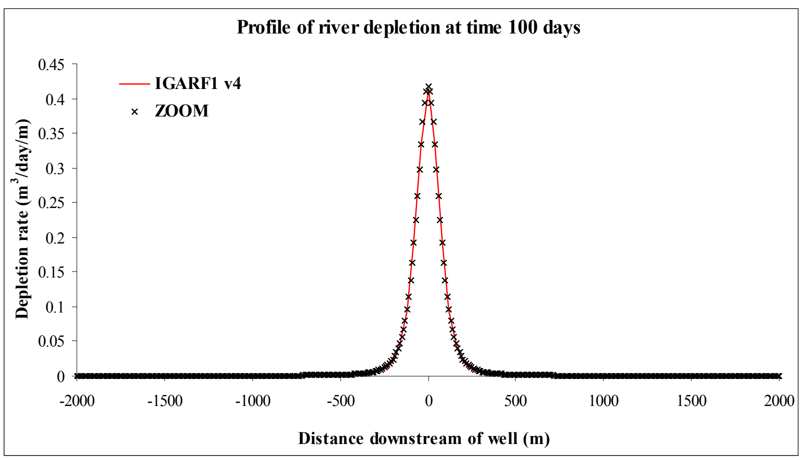

Figure 15 Profiles of river depletion for ZOOMQ3D comparison 4

5 Numerical accuracy of the spreadsheet

The IGARF1 v4 spreadsheet can be used to investigate a vast number of different aquifer configurations by varying the position of abstraction boreholes with respect to rivers and no-flow boundaries, and by altering the geometry and hydraulic characteristics of the aquifer. The tests in this section represent a relatively small number of examples but illustrate some of the problems encountered during the use of the tool.

Groundwater systems are modelled which both broadly approximate UK aquifers types and which include features that incorporate extreme parameters or represent untypical situations.

5.1 TEST 1: TWO HUNT RIVERS 10KM APART, ABSTRACTION BOREHOLE HALF WAY BETWEEN RIVERS

This model includes an abstraction well that is located half way between two Hunt type rivers. The distance between the rivers is 10 km and the parameters assigned to the aquifer approximate a high transmissivity-low storage system i.e. a transmissivity of 1000 m^2 day^{-1} and a storage coefficient of 1%. The model data set is shown in Figure 16. The evolution of river depletion is monitored over the reaches from 2 km upstream to 2 km downstream of the pumped well.

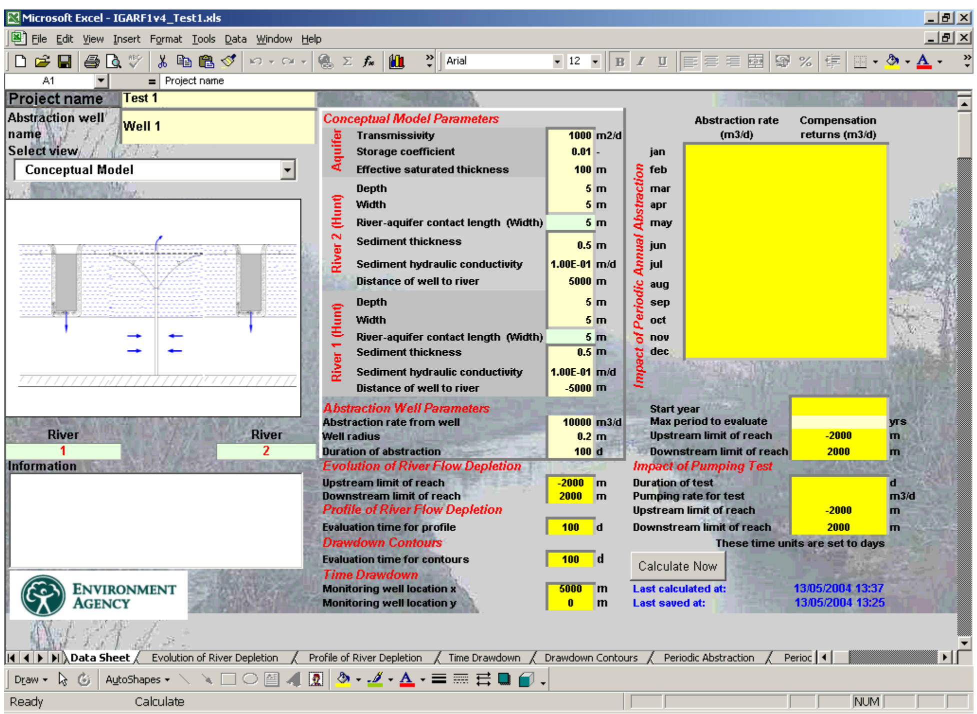

Figure 16 Test 1 Data Sheet

On calculating the solution it is found that the message box appears warning of numerical accuracy issues. The *rdf functions* sheet is shown in Figure 17 and this shows that the 'Fourier Series Output' curve falls to zero too rapidly. To remove these errors the following step were made to try to produce an acceptable solution:

1. Increase the Scale Factor to 20000.
2. Increase the Scale Factor to 30000. This removed the first warning relating to 'Fourier Transform Output' chart falling too rapidly.
3. Increase the Power parameter to 2. This caused the first warning relating to 'Fourier Transform Output' chart falling too rapidly to return.
4. Increase the Scale Factor to 100000

Though it was possible to stop the first warning to occur it was not possible to stop the tool from presenting the following message, which is shown in Figure 18.

> WARNING: The impact of the two river system is not being resolved and the single river solutions for each river are being returned! Refer to the 'Numerical Parameters' section on the 'rdf functions' worksheet to determine whether an inappropriate Scale Factor is being used

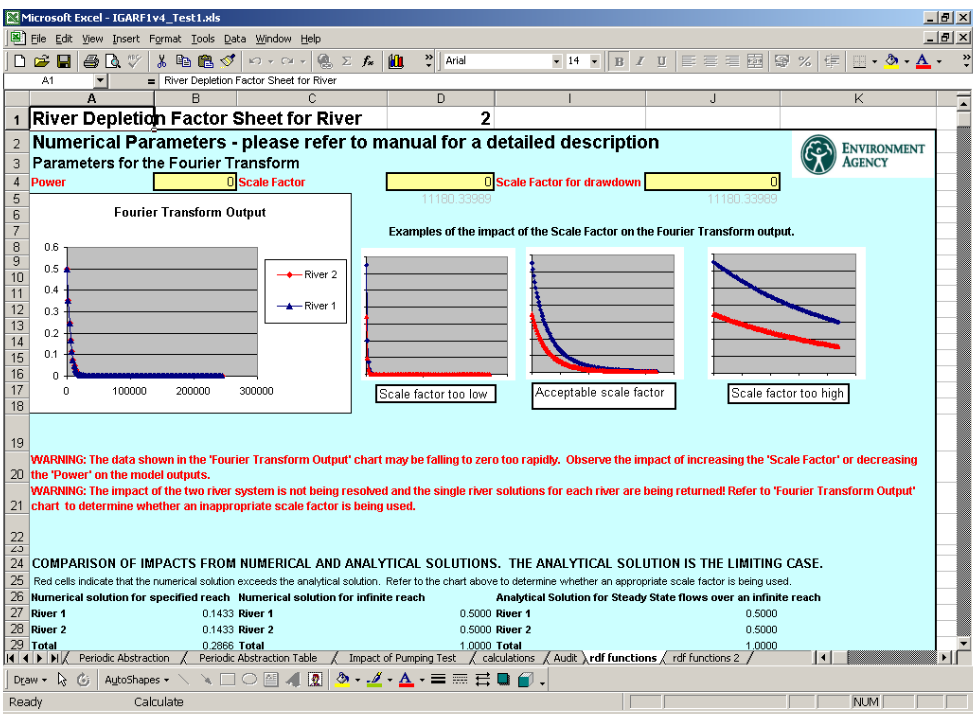

Figure 17 Test 1 rdf functions sheet

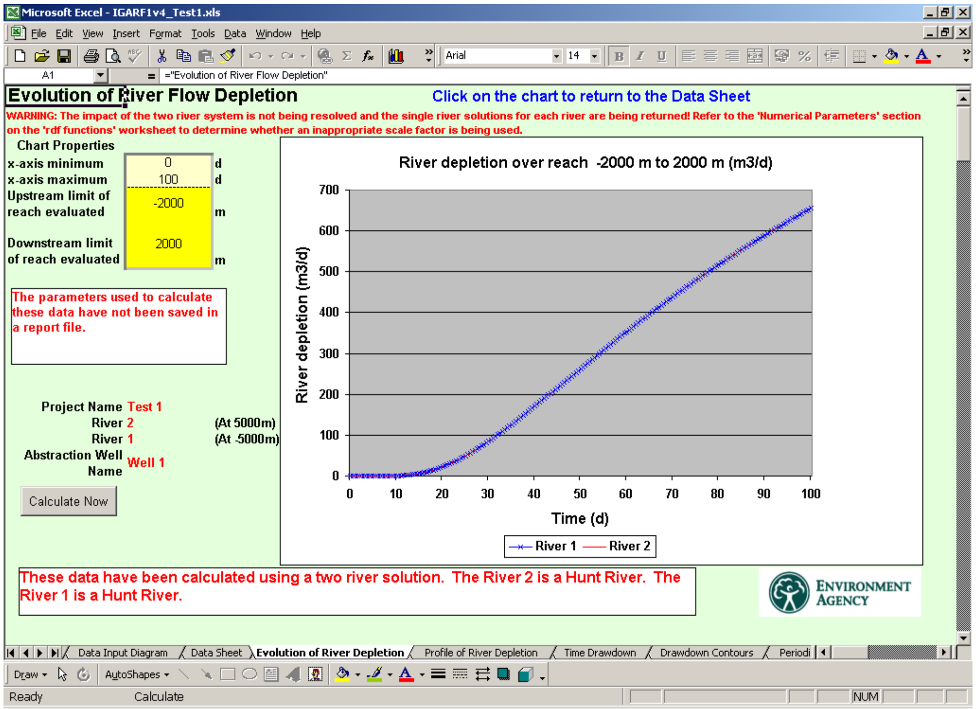

Figure 18 Test 1 Evolution of River Depletion sheet

5.2 SENSITIVITY ANALYSIS USING TEST 1

To examine the influence of some of the model parameters on the occurrence of numerical accuracy warnings a limited sensitivity analysis was performed using the Test 1 model. Each of the parameters on the *Data Sheet* was modified in turn and the effects on the solution observed. These changes are outlined in Table 2.

Table 2 Summary of Test 1 sensitivity analysis

Change made	**Original value**	**New value**	**Effect of change**	**Warnings persist**
Reduce transmissivity ten times	1000	100	Warning remained: returning of the single river solution for both rivers	☒
Increase storage coefficient ten times	0.01	0.1	Warning remained: returning of the single river solution for both rivers	☒
Decrease storage coefficient ten times	0.01	0.001	With Power=Scale Factor=0 'Fourier Series Output' chart falls to zero too rapidly. Increase Scale Factor to 5000 removes all warnings	
Increase saturated thickness ten times	100	1000	Warning remained: returning of the single river solution for both rivers	☒
Decrease saturated thickness ten times	100	10	Warning remained: returning of the single river solution for both rivers	☒
Increase river depth ten times	5	50	Warning remained: returning of the single river solution for both rivers	☒
Increase river width ten times	5	50	Warning remained: returning of the single river solution for both rivers	☒
Halve distance to rivers	5000	2500	Increase Scale Factor to 20,000 removes warnings	
Reduce distance to both rivers	5000	100	Increase Scale Factor to 10,000 removes warnings	

In general for this aquifer configuration the warning relating to the single river solution being returned for each river remained in most of the cases described in Table 2 and could not be resolved by adjusting the Scale Factor and Power parameters on the *rdf functions* sheet. However, no warning messages were presented when the storage coefficient was reduced by a factor of ten or when the distance between the rivers, and thus between the rivers and the well, was reduced.

5.3 TEST 2: TWO HANTUSH RIVERS 10KM APART, ABSTRACTION BOREHOLE HALF WAY BETWEEN RIVERS

Test 2 is a repeat of Test 1 but with Hantush type rivers used instead of Hunt type rivers. All other model parameters are the same. As with Test 1 the Scale Factor and Power parameter were adjusted but it was not possible to stop the warning, relating to the returning of the single river solution for both rivers, from appearing. A Scale Factor of 50,000 was required to stop the 'Fourier Series Output' chart from falling to zero too rapidly (Figure 20).

This warning message still occurred when the reach length over which the evolution of river depletion was calculated was reduced to 100 m upstream and downstream of the abstraction borehole as shown in Figure 21.

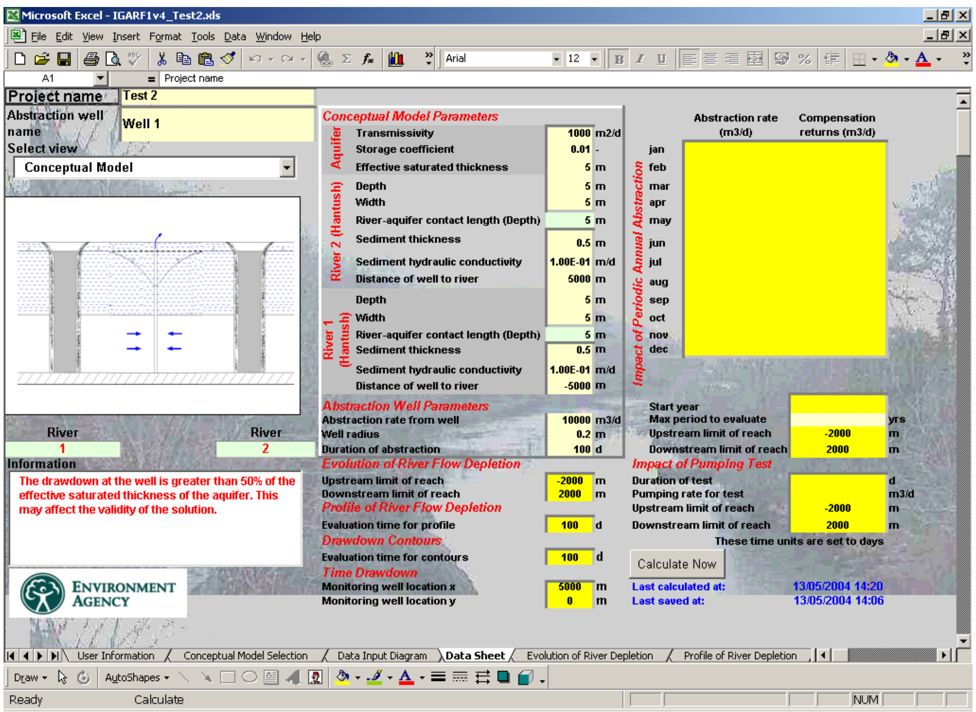

Figure 19 Test 2 Data Sheet

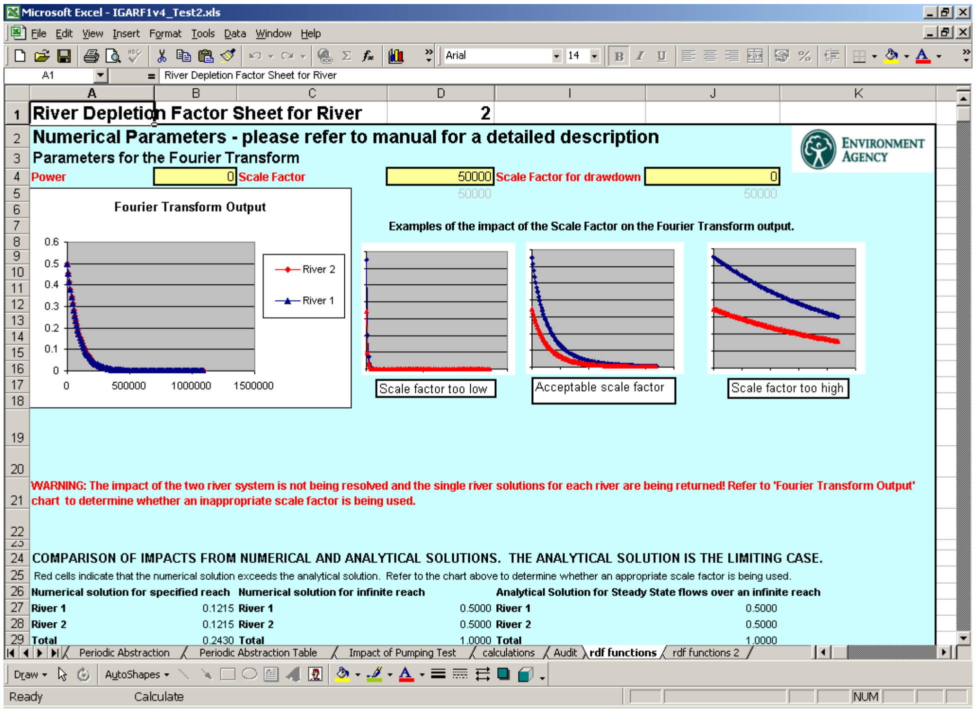

Figure 20 Test 2 rdf functions sheet

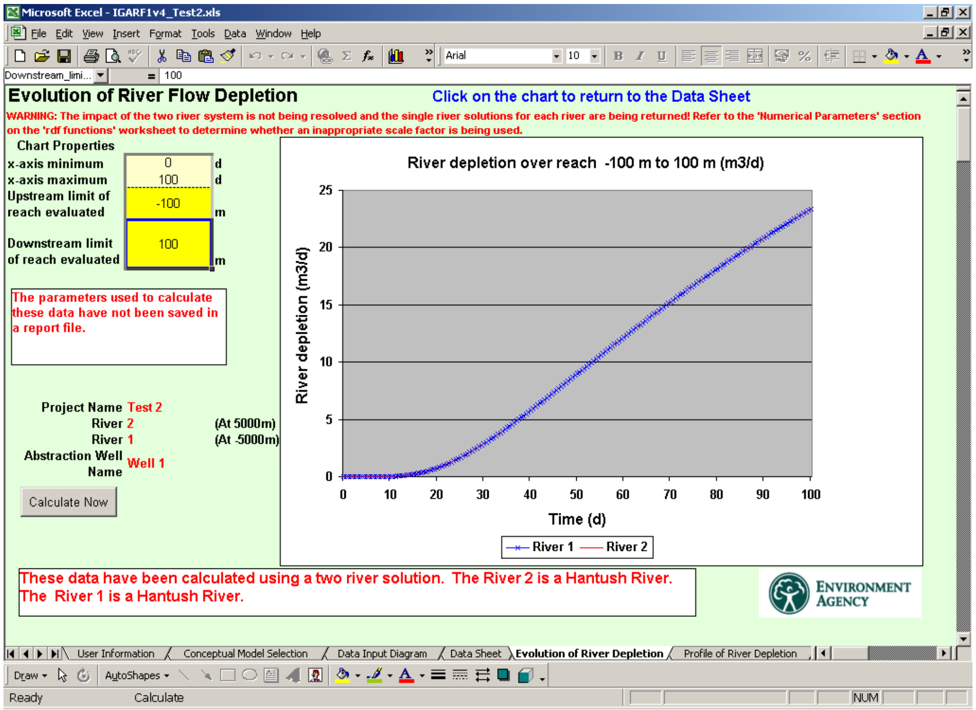

Figure 21 Test 2 Evolution of River Flow Depletion sheet

5.4 TEST 3: TWO THEIS RIVERS 10KM APART, ABSTRACTION BOREHOLE HALF WAY BETWEEN RIVERS

Test 3 is a repeat of Test 1 but with Theis type rivers used instead of Hunt type rivers. All other model parameters are the same. Again, as with Test 1 the Scale Factor and Power parameter were adjusted but it was not possible to stop the warning, relating to the returning of the single river solution for both rivers, from appearing.

The *Data Sheet* and model output are shown in Figures 22 to 24.

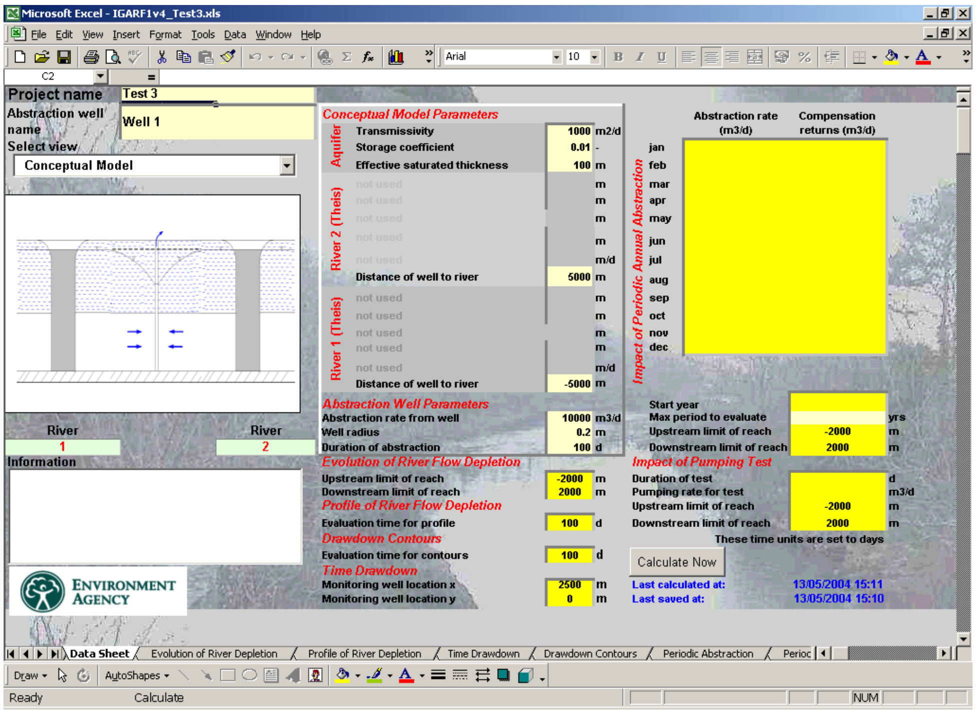

Figure 22 Test 3 Data Sheet

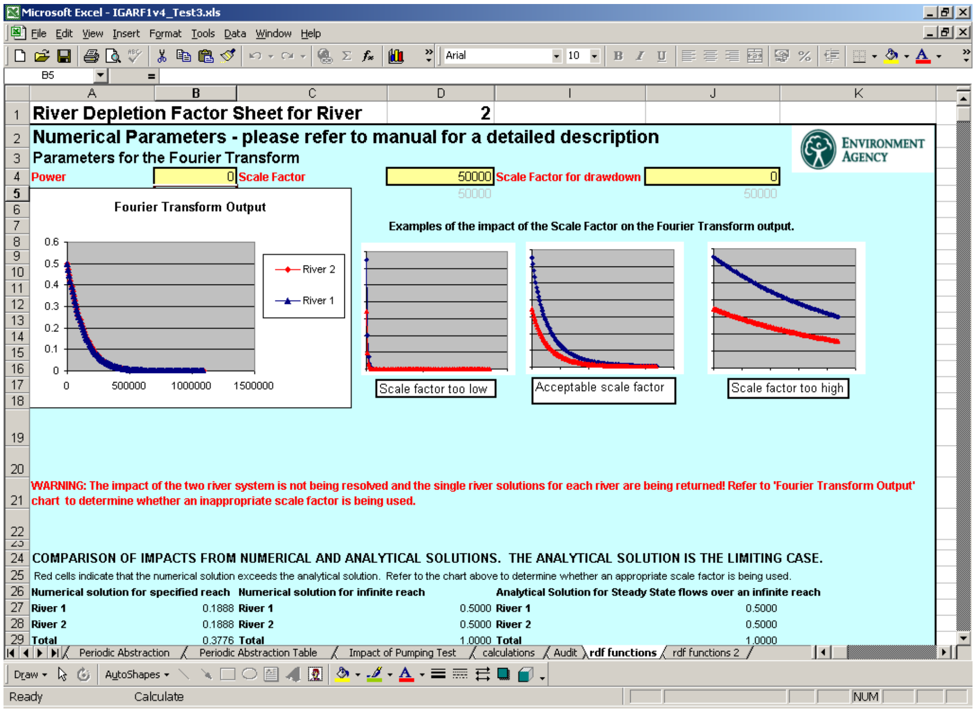

Figure 23 Test 3 rdf functions sheet

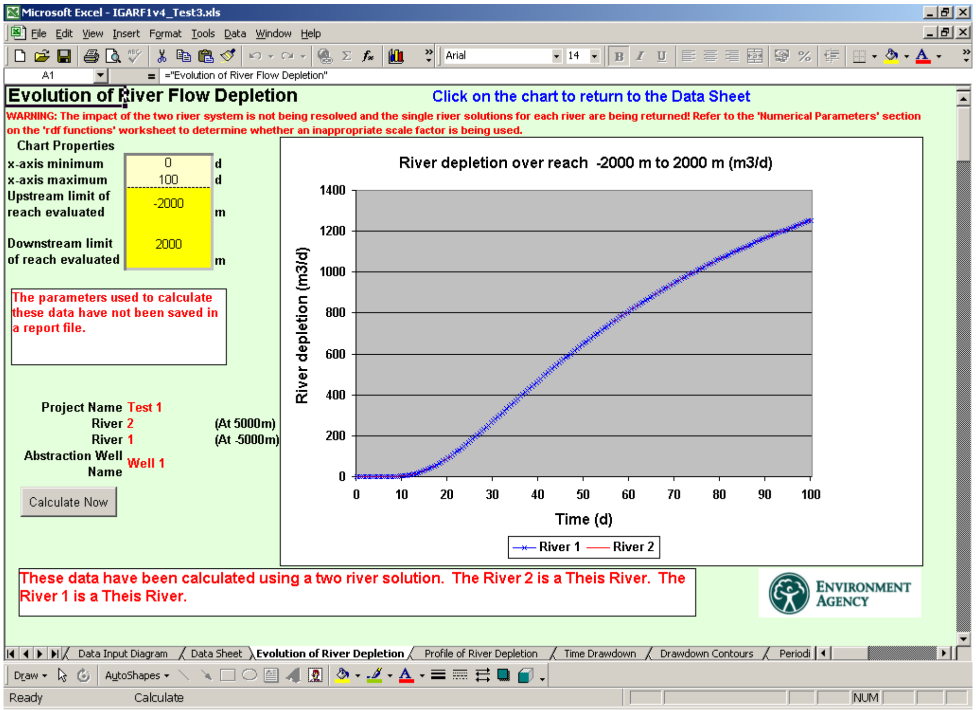

Figure 24 Test 3 Evolution of River Flow Depletion sheet

5.5 TEST 4: TWO HUNT RIVERS 4 KM APART, ABSTRACTION BOREHOLE HALF WAY BETWEEN RIVERS

This model again included an abstraction well that is located half way between two Hunt type rivers. The distance between the rivers is 10 km and the parameters assigned to the aquifer approximate a low transmissivity-high storage aquifer system i.e. transmissivity of 100 m^2 day^{-1} and storage coefficient of 15%. The model *Data Sheet* is shown in Figure 25. The evolution of river depletion is monitored over the reaches from 2 km upstream to 2 km downstream of the pumped well.

As with Test 1 and 2, the Scale Factor and Power parameter were adjusted but it was not possible to stop the warning, relating to the returning of the single river solution for both rivers, from appearing.

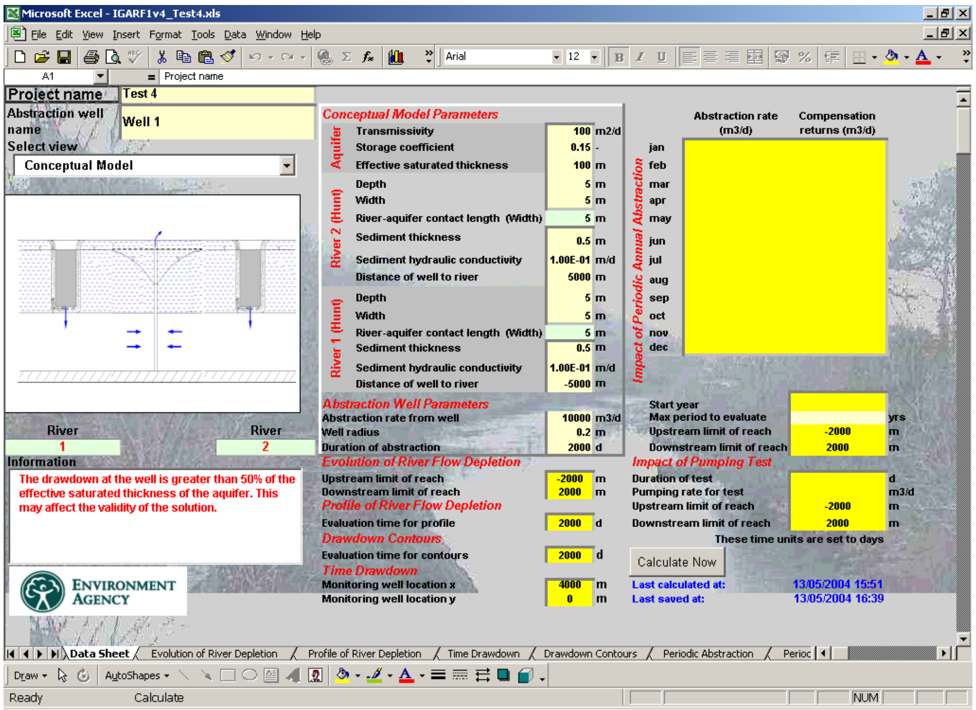

Figure 25 Test 4 Data Sheet

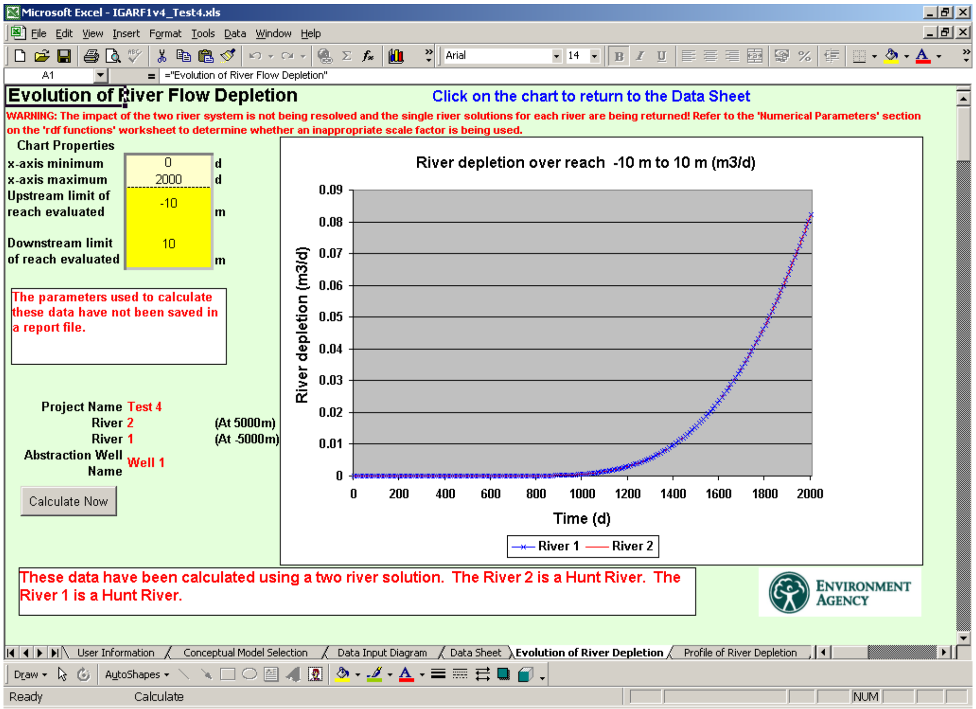

Figure 26 Test 4 Evolution of River Flow Depletion sheet

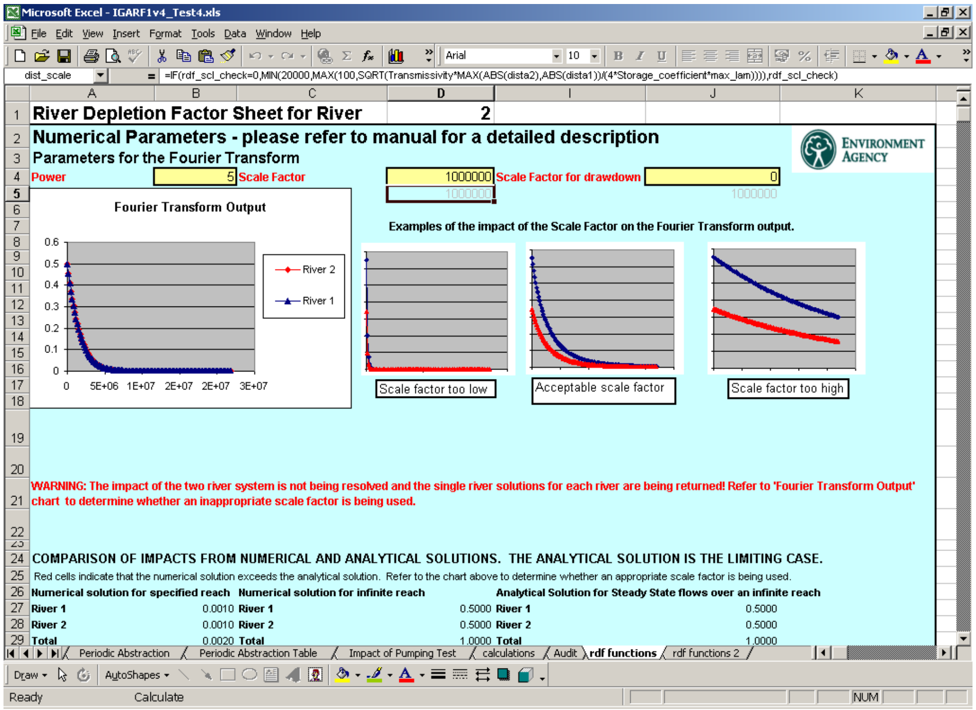

Figure 27 Test 4 rdf functions sheet

5.6 TEST 5: HANTUSH RIVER - WELL - NO-FLOW BOUNDARY SYSTEM

In this test an IGARF spreadsheet model is constructed using the data shown in Figure 28. In this system the pumped well is located 10 m from a Hunt type river and 1 km from a no-flow boundary. The initial model has a low transmissivity of 50 m^2day^{-1} and low storage of 0.1%, however, each of the aquifer and river parameters is adjusted in turn to examine the effect on the robustness of the solution process i.e. to investigate when and how often warning messages are presented to the user.

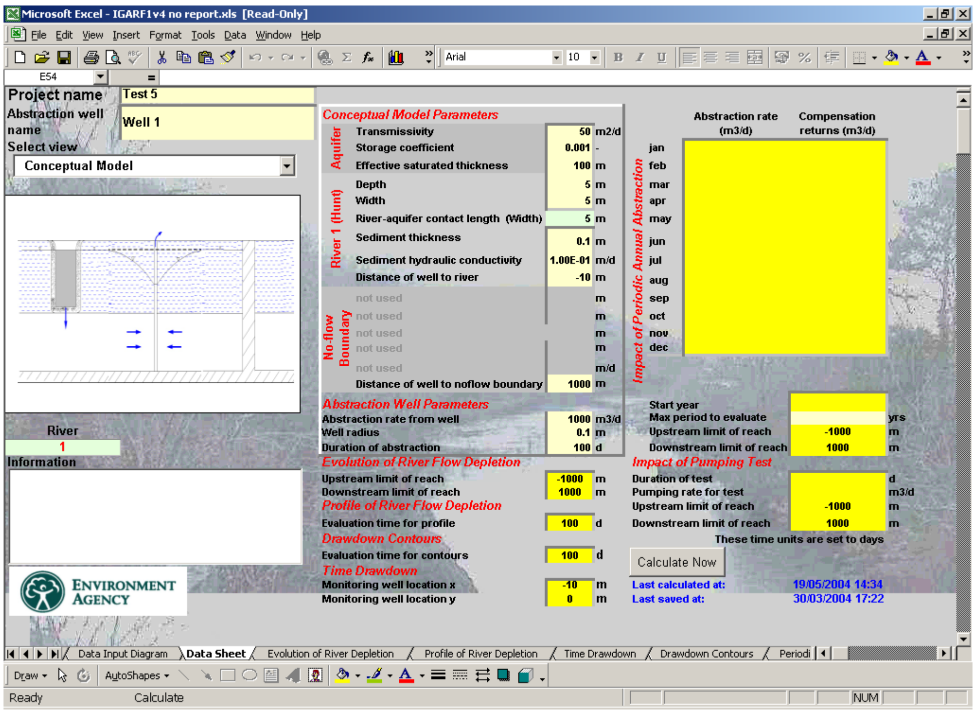

Figure 28 Data Sheet for Test 5 spreadsheet model

The changes to the model parameters and their effects on the solution are listed in Table 3. In general when simulating this low transmissivity and storage system, in which the pumped well is close to the river, few warnings are presented to the user that cannot be corrected by adjusting the Scale Factor. In this case the numerical solution process only failed to produce adequate results when an extreme and unrealistic parameter value was used for the river bed sediment thickness i.e. 0.001 m. This is not likely to used in practice but if required this warning could be circumvented by using a high river bed hydraulic conductivity instead.

The second problem that was identified was the simulation of an irregular river depletion profile 10 days after the cessation of pumping. This is shown in Figure 29. Whilst this is not accurate, the depletion rates at this time are so small that it is not of great importance.

Table 3 Summary of Test 5 model parameters adjustment process and warnings

Original parameter set shown in Figure 28	Warning produced relating to too rapid fall of Fourier Series Output. Easily corrected by increasing Scale Factor.	
Difference from original parameter data set	**Results**	**Warnings persist**
Increase storage coefficient to 0.1	No warnings/errors observed	
Saturated thickness increased and decreased	No warnings/errors observed	
Depth of river increased and decreased	No warnings/errors observed	
River bed sediment thickness increased	Warnings are easily resolved by adjusting the Scale Factor but river becomes disconnected	
Sediment thickness reduced to 0.01 m	Warnings presented in which abstracting more from river than abstraction – corrected using Scale Factor	
Sediment thickness reduced to 0.001 m	Warnings presented in which abstracting more from river than abstraction – Could not correct using Scale Factor and Power parameters	☒
Reduce hydraulic conductivity of river bed to 10-4 $mday^{-1}$	Numerical accuracy warnings occur but are easily resolved by adjusting Scale Factor. River becomes disconnected	
Distance of well to river increase to 1 km.	Warnings easily removed by modifying Scale Factor.	
Reduce distance to no flow boundary to 100 m.	No warnings/errors observed	
Increase abstraction to 5000 m^3day^{-1}.	Warnings easily resolved by modifying Scale Factor.	
Reduce abstraction to 50 m^3day^{-1}.	No warnings/errors observed	
Calculate evolution of river depletion for reach from –100 m to 100 m.	No warnings/errors observed	
Calculate evolution of river depletion for reach from –5000 m to 5000 m.	No warnings/errors observed	
Calculate profile of river depletion 1 day after start of pumping.	No warnings/errors observed	
Calculate profile of river depletion 110 days after start of pumping.	No warnings/errors observed but oscillation in profile of river depletion due to low depletion rates after pumping stops. See Figure 29	☒
Time at which to calculate contours increased and decreased.	No warnings/errors observed	
Location of monitoring well moved perpendicular to river along line of well.	No warnings/errors observed	

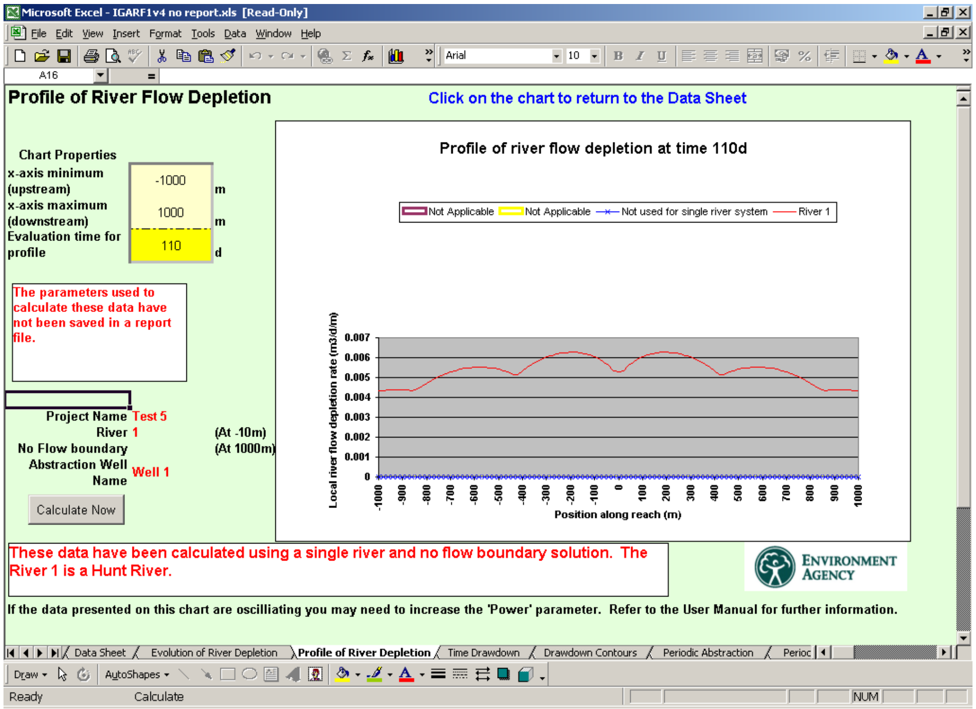

Figure 29 Irregular profile of profile of river depletion during use of Test 5 model

5.7 TEST 6: WELL BETWEEN TWO HUNT TYPE RIVERS

In this test an IGARF spreadsheet model is constructed using the data shown in Figure 30. This is the same system as described in the previous example but with the no-flow boundary being replaced by a second Hunt type river. The pumped well is located 100 m from both rivers. Again the aquifer has a low transmissivity of 50 $m^2 day^{-1}$ and low storage of 0.1%. A single run was performed to see if the introduction of a second Hunt type river caused problem to the solution process. This was not found to be the case.

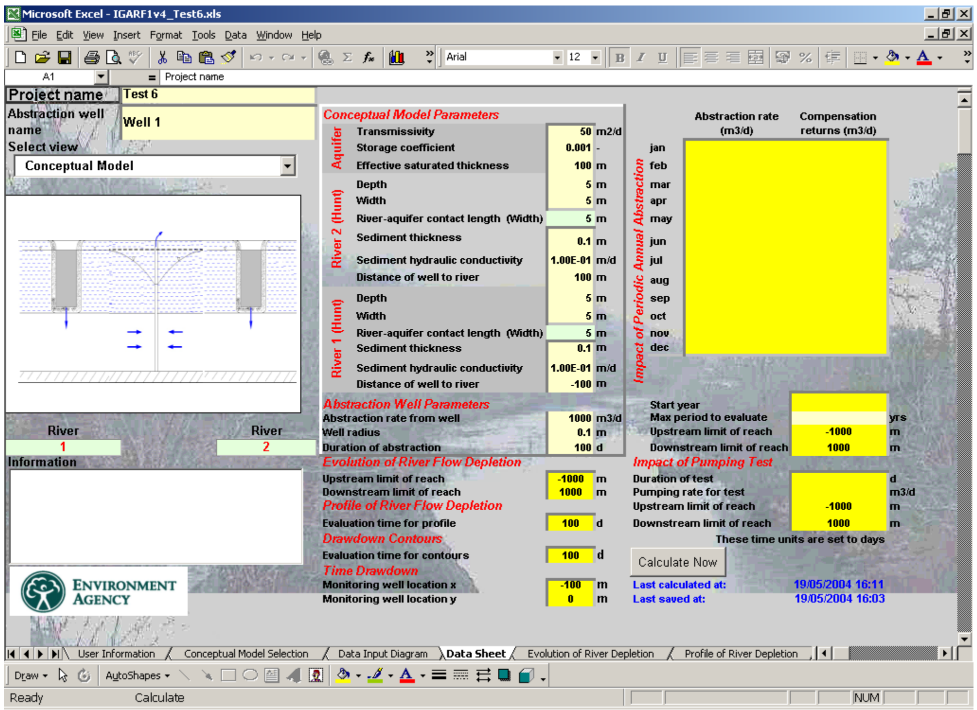

Figure 30 Data sheet for Test 6 model

5.8 TEST 7: PUMPED WELL BETWEEN HUNT AND HANTUSH TYPE RIVERS

In this test a spreadsheet model is constructed using the data shown in Figure 31. In this system the pumped well is located 4 km from a Hunt type river and 4 km from a Hantush type river. The initial model has a high transmissivity of 2000 m^2day^{-1} and storage of 1%, however, as in Test 5, each of the aquifer and river parameters is adjusted in turn to examine the effect on the robustness of the solution process i.e. to investigate when and how often warning messages are presented to the user.

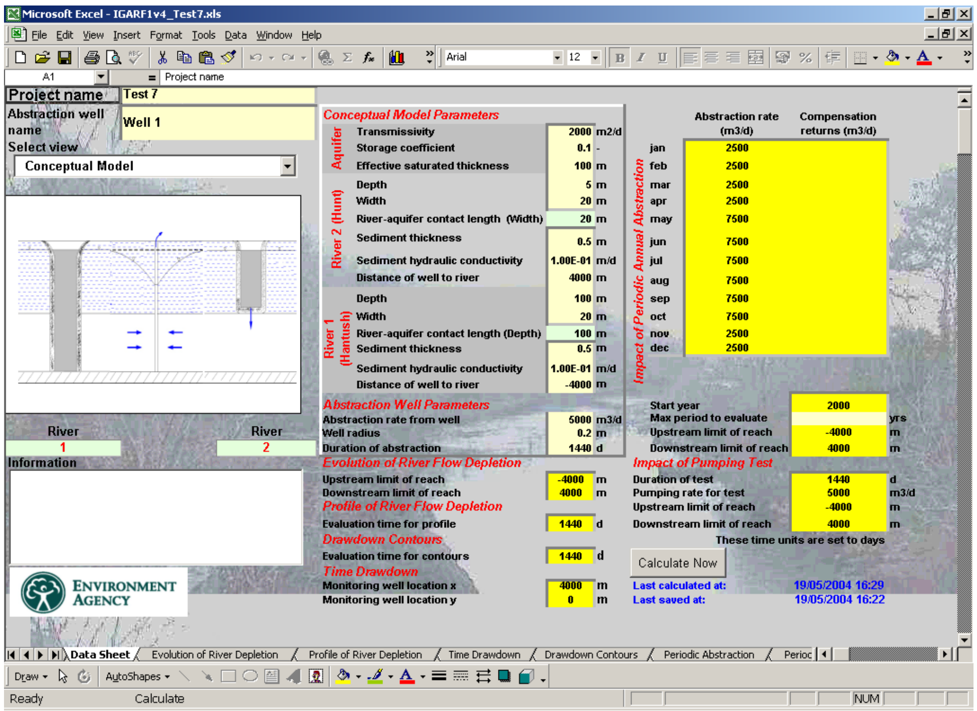

Figure 31 Data Sheet for Test 7 model

The changes to the model parameters and their effects on the solution are listed in Table 4. In all but three of the eleven simulations performed using this model, it was the case that either no warnings or errors were observed, or when warnings were presented they could easily be resolved by adjusting the Scale Factor and Power parameters.

However, the numerical solution process failed to produce adequate results in three cases, one of which represents a realistic system. When the transmissivity was reduced to 500 m^2day^{-1} two types of warnings were presented which could not be resolved by adjusting the Scale Factor and Power parameters. These relate to the rapid fall of the Fourier Series Output for both rivers and to the single river solution being returned for each river for the evolution of river depletion.

These warnings were also presented and could not be resolved by adjusted the Scale Factor and Power parameters when the river bed conductivity was reduced to below 10^{-3} $mday^{-1}$.

Table 4 Summary of Test 7 model parameters adjustment process and warnings

Original parameter set shown in Figure 31	Warning produced relating to too rapid fall of Fourier Series Output. Easily corrected by increasing Scale Factor to 20000.	
Difference from original parameter data set	**Results**	**Warnings persist**
Transmissivity increased to 4000 m^2day^{-1}	No warnings/errors observed	
Transmissivity decreased to 500 m^2day^{-1}	Warning presented: The impact of the two river system is not being resolved and the single river solutions for each river are being returned! … Failed not stop warning by adjusting Scale Factor and Power.	☒
Storage coefficient reduced to 0.01	No warnings/errors observed	
Storage coefficient reduced to 0.001	No warnings/errors observed	
Storage coefficient increased to 0.25	No warnings/errors observed	
Saturated aquifer thickness and depth of Hantush type river reduced to 10 m	No warnings/errors observed	
Sediment hydraulic conductivity of Hantush type river reduced to 10^{-4}	Two types of warnings are presented which could not be resolved by adjusting the Scale Factor and Power parameters. These relate to the rapid fall of the Fourier Series Output for both rivers and to the single river solution being returned for each river for the evolution of river depletion.	☒
Sediment hydraulic conductivity of both rivers reduced to 10^{-3}	Warning presented: The impact of the two river system is not being resolved and the single river solutions for each river are being returned! … Failed not stop warning by adjusting Scale Factor and Power.	☒
Abstraction increased to 10,000 m^3day^{-1}	No warnings/errors observed	
Abstraction reduced to 100 m^3day^{-1}	No warnings/errors observed	

6 Conclusions

The IAGRF1 v4 spreadsheet tool has been found to be a Powerful and easy to use application that generally produces accurate results rapidly. However, during the testing process problems have been encountered, some of which could be considered serious.

The testing process has been broken down into a number of tasks, the first of which was to replicate the use of the spreadsheet as it is described in Section 5 of the IGARF1 v4 User Manual i.e. to reproduce the River Otter case study. This has been done using both versions of the Excel spreadsheet (IGARF1v4.xls and IGARF1v4 no report.xls) and no differences have been observed between the modelled results and those presented in the User Manual.

Three 'bugs' have been encountered which relate to coding issues or to features of the spreadsheet. These relate to:

1. what appears to be problems associated with the dll, which contains the analytical solutions. The spreadsheet has crashed a number of times (less than ten) when the *Calculate Now* button has been pressed. In these cases a Windows pop-up error message is presented which indicates that there has been a memory access error. It is suspected that this is likely to be a problem with the code contained in the dll, but it could be an error within an Excel macro.
2. copy and pasting values between data entry cells in the spreadsheet. This can cause the rules, which are associated with the values that are allowed in the cells, to be corrupted. If this is not considered as a bug it should be recommended that users should use *Copy➔Paste Special➔Values*.
3. the drop down box on the *Periodic Abstraction* sheet, which is not protected and can be deleted.

Four models have been constructed using both IGARF1 and ZOOMQ3D (Jackson, 2001) and a comparison has been made between the results of each. In all cases the results have been in close agreement, except for the model in which the river becomes perched due to the abstraction. The analytical solutions do not represent the perching of river. As expected drawdowns are greater and river depletion rates lower in the numerical model.

The use and testing of the spreadsheet has illustrated that in most cases it returns accurate results. In general it is straightforward to obtain the correct results, however, in approximately 50% of model runs, the Scale Factor and Power parameters, on the *rdf functions* sheet, had to be adjusted to resolve the warning messages that are presented after the solution is calculated.

In most cases the warning messages can be resolved quickly, generally by adjusting the Scale Factor parameter only. However, for some models it was not possible to resolve the warning messages by adjusting either or both of the Scale Factor and Power parameters. The most frequently occurring warning that could not be resolved, was:

> *WARNING: The impact of the two river system is not being resolved and the single river solutions for each river are being returned! Refer to the 'Numerical Parameters' section on the 'rdf functions' worksheet to determine whether an inappropriate Scale Factor is being used*

This warning relates to the evolution of river depletion over time and always occurred in the models containing a well, located half way between two rivers, (see sections 5.1. to 5.4 and 5.8), in

- an aquifer with transmissivity of 1000 m^2day^{-1} and a storage coefficient of 1% with rivers 10 km apart,
- an aquifer with transmissivity of 100 m^2day^{-1} and a storage coefficient of 15%, with river 10 km apart.

These are realistic parameters for UK aquifers but the message also occurred in the model of:

- an aquifer with transmissivity of 2000 m^2day^{-1} and a storage coefficient of 10%, with river 8 km apart (see Section 5.8).

Numerous other aquifer and river / well configurations have been simulated for which no warnings or errors were observed, except when setting extreme parameter values e.g. the river sediment thickness to 10^{-3} m in Test 5 (Section 5.6). However, in Test 7 (Section 5.8) it was not possible to resolve the warning messages when the river-bed sediment hydraulic conductivity of the two rivers was reduced to 10^{-3} $mday^{-1}$. This is not an unrealistic value for river bed permeability.

Whilst the numerical warnings occurred frequently, the appropriate warnings were always presented at the appropriate time. These warnings are well presented and make it easy for the user to attempt solve the problem. However, in terms of the ease of use of the tool, perhaps one improvement that could be made, would be to implement a button on the *rdf functions* worksheet that returns the user to the *Data Sheet*. This is minor point though and the spreadsheet was found to be well laid out, clear and easy to understand.

There are a couple of issues that should be considered when preparing the tool for release to organisations external to the Environment Agency. The first consideration relates to the applicability of the model. External users should be made fully aware of its limitations and of the need to carefully check the accuracy of the model results. This is a minor point, however, a more serious issue relates to the robustness of the dll, which has caused the tool to crash. The dll should be rigorously debugged before the tool is made freely available. Once this has been achieved the development of the spreadsheet should be publicised and disseminated widely to enable other hydrogeologists to test their conceptual understanding of simple groundwater systems readily.

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