Water Management Plan for Gaens' Quarry

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PREFACE

Gaens' Quarry is currently the subject of an Environment Act 'ROMP Review' which will update the planning conditions controlling future operations at the Quarry. The Applicant, TS Rees Ltd, has proposed a series of updated planning conditions as required by the Review, including a commitment to carry out the development in accordance with a 'Water Management Plan' (WMP).

Several versions of the WMP have previously been submitted; initially as part of a previous ROMP Environmental Statement for Cornelly Quarry (WynThomasGordonLewis, 2004), with several subsequent versions being prepared to take into account comments made by the Environment Agency, the Countryside Council for Wales (now combined into Natural Resources Wales) and other interested parties.

On 3 March 2013 the Welsh Government issued a Scoping Direction for a new Environmental Statement (ES) under the 'Stalled ROMP Regulations' (ref A-PAA-25-08-004t). As a result the quarry oprator prepared a new ES which showed that, assuming some residual pumping was carried out at the end of active working, the proposed development would not cause a 0.1 m change in groundwater levels in the blown sands at Kenfig SAC over three consecutive years (the agreed hydrological criterion for these potentially sensitive features for the purposes of assessing impacts on the integrity of the Kenfig SAC).

The Scoping Direction also included a requirement to prepare a revised WMP:

> *The ES should include a refinement of the water management plan, which should include a description of water management measures at the quarries, linked to the proposed works, quarry development, quarry decommissioning and reinstatement and set out the monitoring programme, a description of any necessary remedial strategy and any actions the operator would take to prevent and/or reverse any impacts. This should facilitate the improved understanding of the regional and local water regime and the nature of any uncertainty which might remain.*

As a result, in 2014 the Quarry Operators prepared a substantially revised WMP (v5.0) to comply with the Scoping Direction and in light of the results of the new ES for the Quarry (SLR, 2014). This final version of the WMP (v5.8) has been prepared in response to comments received on v5.0 from Natural Resources Wales in early 2015 (letter to Welsh Government dated 18 Sept 2014 - Cornelly, Grove and Gaens Quarry ROMP Geoscience comments on Environmental Statements (SLR, June 2014)) and comments on the subsequent v5.1 WMP (ESI, April 2015) issued on 14 May 2015. v5.3 (ESI, July 2015) received on 31 July 2015[1] and some final iterations as part of the process of agreeing a Statement of Common Ground prior to the Public Inquiry in November 2015, in order to ensure impacts on the Kenfig Dunes SAC are avoided.

It is anticipated that this refined WMP will be cross referenced in a final version of a schedule of planning conditions which will be imposed by the determining Authority (Welsh Government).

[1] An interim v5.2 version was discussed at a meeting between Natural Resources Wales and ESI on 13 July 2015.

1 DEFINITIONS

Appropriate Calculations are defined in Section 6.7.

Assessment Criteria are 'standards' against which data can be compared in order to assess whether there has been a Deviation from the behaviour at that site relative to the behaviour that would be anticipated under 'natural'[2] conditions. There are two types of Assessment Criteria:

- Trigger Levels are defined in Section 6.2.1.
- Climate Based Assessment Criterion is defined in Section 6.3.1 and Climate Based Assessment Criteria will be interpreted accordingly.

A **Deviation** is considered to have occurred when the data at a site 'exceeds' an Assessment Criterion by a particular amount:

- Deviation from a Trigger Level Assessment Criterion is defined in Section 6.2.1.
- Deviation from a Climate Based Assessment Criterion is defined in Section 6.3.1.

The definition of a **Significant Deviation** is set out in Section 6.4.

Sensitivity Criteria are defined in Section 6.4.

Critical monitoring sites shall include:

- At least one pathway site monitoring the bedrock aquifer between the quarries and each of the SACs (Kenfig and Merthyr Mawr);
- The monitoring sites required to define the water balance within each quarry (this may include sump levels as well as various pumping rates)..

  Critical monitoring sites are identified in Appendix A. The list of Critical Monitoring sites can be amended as part of the annual review if trends are occurring ina particular area that require particular attention.

There are two types of **'mitigation measures'** applied under this WMP:

- **Planned Mitigation Measures** are those actions described in Section 7.1 that have been considered in the Environment Statement (SLR, 2014) and which have been shown in that document to be effective at mitigating any small hydrological effects that might be caused by the operation of the quarry at potentially sensitive receptors.
- **Contingency Measures** are defined in Section 8. Contingency Measures are actions that should be taken if potentially significant events occur in and around the quarry for which Planned Mitigation Measures were not specifically considered as part of the Environmental Statement. Contingency Measures can also be required in the event of a major failing in part or all of the monitoring network.

Source is defined in Section 4.1.

Pathway is defined in Section 4.1.

Receptor is defined in Section 4.1.

The **Quarry Operator** means the Company that operates Gaens' Quarry.

The **Regulator** means the public body that is responsible for ensuring that the activities that the Quarry Operator is required to carry out under this Water Management Plan (WMP) are carried out. On formal adoption of the WMP this will be Bridgend County Borough Council.

[2] There is a wide range of possible mechanisms that can cause variation from 'natural' conditions. Where these cannot be easily distinguished using the available data, Appropriate Calculations (Section 6.7) may be needed to estimate the relative significance of different potential causes.

2 INTRODUCTION

2.1 Background

Gaens Quarry (the “Quarry”) is located to the east of South Cornelly village, between the towns of Pyle and Porthcawl. The quarry works Carboniferous Limestone which is used in part to supply a lime works at Miskin. Additional markets include the steel and foundry industries, together with general aggregate usage. The total area covered by existing consents for mineral extraction at the Quarry is approximately 13 ha.

The main quarry floor is currently at around 30 to 35 mAOD. There are two main sumps which are used to work lower benches: the eastern sump is excavated to around 20 mAOD with a water level of around 24 mAOD, while the central sump is excavated to around 21 mAOD with a water level of around 29 mAOD. Water is intermittently pumped from these sumps to a sump in the north west of the quarry where it soaks away.

It is planned that the Quarry will ultimately be worked to –20 mAOD in line with the existing planning permission.

2.2 Planning Context

In 1997, applications were made to Bridgend County Borough Council under the Environment Act, 1995 (Review of old mineral permissions – ROMP), for determination of a scheme of conditions in respect of the area of the Quarry covered by those planning permissions (the “ROMP application”). Separate applications were made in respect of the nearby Cornelly and Gaens’ Quarries. The applications were referred to the Secretary of State for Wales in May 1998 (Gaens’) and July 1998 (Cornelly and Grove). Due to the commonality of issues at these sites, it was decided that they should be determined as a group. The National Assembly for Wales (now the Welsh Assembly Government) subsequently took on the role of determining authority for the applications.

An Environmental Impact Assessment (EIA) in connection with the ROMP application for the Quarry was undertaken voluntarily, and an Environmental Statement (ES) setting out the results of the EIA was submitted in 2004 (White Young Green, 2008). This included an earlier version of this WMP that was subject to extensive consultation with the relevant regulators at that time.

For reasons explained in Chapter 1.0 of the main ES (SLR, 2014), the respective applications have not been determined, and there is a requirement to undertake further updated EIAs and to present the results in updated formal ESs. The hydrological and hydrogeological elements of the EIA were based on the continuation and extension of current water management practices at the Quarry. A summary of the Hydrogeological ES is contained at Appendix F.

The ES includes a set of proposed planning conditions, including a requirement to continue the quarrying operations in accordance with a Water Management Plan (WMP), (ref SLR, 2014 Annex 1).

2.3 The Water Management Plan

The objective of the WMP is to guide the Quarry Operator in its management of water at the Quarry such that any adverse environmental impacts resulting from these activities can be minimised. In particular the water management plan has been devised to ensure that there is no impact on the integrity of the Kenfig SAC as a result of quarry dewatering. In order to achieve this, the WMP will:

- Specify the monitoring activities required;
- Outline how the resultant data should be reviewed in order to determine whether the operation of the Quarry has affected any of the monitoring sites;

- Outline the options for management of water at the Quarry and how these could be adjusted in the light of any effects detected at any of the monitoring sites.

The Quarry Operator will operate the WMP until the ongoing monitoring and reporting under the WMP demonstrates that the need for Planned Mitigation Measures as a result of the activities at the Quarry has ceased[3].

The determining authority under the ROMP procedure, and hence this document, is the Welsh Government, with Bridgend County Borough Council and Natural Resources Wales as statutory consultees. Following determination of the ROMP and formal adoption of the WMP, the regulatory body will become Bridgend County Borough Council (the Regulator) with Natural Resources Wales as statutory consultee.

Due to the commonality of issues, conditions for the adjacent Cornelly and Grove Quarries will be determined in parallel with those for Gaens Quarry. As a result, a separate WMP will be required for each quarry. Whilst there is a significant degree of overlap between the WMPs for the three quarries, they each form separate and independent documents. However, the respective WMPs are being prepared by the same hydrogeological consultant, using common data, the collection, analysis and interpretation of which has been jointly funded by the respective Quarry Companies.

2.4 This Document

This final version of the WMP (v5.3) updates the draft WMP (v5.0) that was submitted as part of the 2014 ES for the Quarry (SLR, 2014) and has been revised to take into account comments by Natural Resources Wales (18 Sept 2014 - Cornelly, Grove and Gaens Quarry ROMP Geoscience comments on Environmental Statements (SLR, June 2014)) and comments on the subsequent v5.1 WMP (ESI, April 2015) issued on 14 May 2015[4].

Figure 1 provides a flow diagram illustrating the main processes required in the WMP. Figure 2 illustrates some of the general timelines and also draws together some of the key response times. These are for illustrative purposes only. The main text of this report provides the definitive description of the requirements of the WMP.

2.5 Future Amendments

It is intended that the WMP will be a 'living document' and will be operated over many years during which there are likely to be staff changes at both the Regulator and the Quarry Operator. It is important therefore that the WMP should be unambiguous and comprehensive. However, it should also contain appropriate mechanisms to allow it to be adapted so that it can continue to be used successfully as conditions change in the future. The inclusion of measures to deal with certain eventualities does not necessarily indicate that such eventualities are viewed as being likely.

It is anticipated that the actions required under the WMP (e.g. monitoring locations, frequencies, mitigation and contingencies etc.) may need to be revised from time to time in the light of data sets obtained and / or other factors affecting either the regulatory or hydrogeological environment. No changes requested by the Regulator shall, however, have the purpose or effect of stopping or preventing quarry operations or otherwise restricting working rights within the meaning of the Environment Act 1995. It is expected that the need for any changes will become apparent as part of the annual reporting cycle (Section 5).

Note that it is expected that water quality standards for the water discharged off site from dewatering activities will be addressed by means of Environmental Permits which will be agreed separately with Natural Resources Wales.

[3] See comments in Section 3.2 about the need for Planned Mitigation Measures to continue after the end of dewatering.
[4] An interim v5.2 version was discussed at a meeting between Natural Resources Wales and ESI on 13 July 2015.

3 WATER MANAGEMENT

3.1 Quarry Pumping (Operational Phase)

At present there is only intermittentpumping from a basal sump in Gaens' Quarry with water being discharged within another part of the quarry. The exact layout of any future dewatering system is not yet clear but is likely to be similar.

The calculations carried out as part of the environmental impact assessment (Appendices 7.3 and 7.4 of SLR, 2014) indicate that average pumping rates from the Quarry will be around:

- 2443 m^3/d at 15 years (-0 mAOD).
- 2352 m^3/d at 42 years (-20mAOD).

These rates assume that Cornelly Quarry continues to discharge primarily to Grove Quarry. If Cornelly Quarry reverts to pumping to Pant Mawr quarry, then the rate required to dewater Gaens Quarry will increase.

These are average rates: clearly the rates required at any one time will depend on antecedent rainfall and quarry operational factors. The monthly average rate of pumping previously has varied by +/- a factor of two.

It is anticipated that, in future, the amount of variability around the mean monthly average rate is likely to be similar to that experienced in the past. Where the pumping rate in the Quarry is significantly higher than that which would be expected given antecedent rainfall and quarry operations, this would trigger Contingency Measures (Section 8).

3.2 Quarry Pumping (Recovery Phase)

The period during which the quarry void fills with water after the end of quarry operations and dewatering has been identified in the ES as a period with potential for impact on surrounding water bodies, unless Planned Mitigation Measures continue during the period required to restore groundwater equilibrium. The need to consider continued pumping out of the Quarry (albeit at lower rates) during this period until conditions have broadly stabilised is noted in the ES. The WMP has been written in a manner that will allow it to continue to guide the management of water on site during this period.

3.3 Discharge of Dewatering Water

From the processing water lagoon, water is pumped off site as required. There are three routes currently available for disposal of this water from the Quarry:

1. Pumping to northern quarry sump

In the future it is possible that other options for the disposal of dewatering water may arise.

4 MONITORING REQUIREMENTS

4.1 Normal Monitoring Procedures

The Quarry Operator shall ensure that monitoring is carried out at the sites set out in Appendix A - Sections A.1, A.2, A.3 and A.4 of this WMP at the frequencies specified therein. The methods required to ensure the accuracy and representativeness of the data collected are set out in Appendix B.

Procedures for managing any problems that it is anticipated could prevent the Quarry Operator from carrying out the required monitoring are set out in Section 4.1.3. The Quarry Operator and Regulator will work together to ensure that the functional integrity of the monitoring network is maintained.

4.1.1 Classification of sites

In Appendix A, monitoring sites have been classified according to the purpose of monitoring at that site[5]:

- Source (monitoring of activities in and around the Quarry that could give rise to impacts on the surrounding groundwater systems – principally dewatering and disposal of water)
- Pathway (monitoring of sites between the Quarry and potential receptors to provide early warning of potential impacts)
- Receptor (monitoring of hydrogeological conditions at a potentially sensitive site)
- Background (monitoring that provides information that helps interpret trends observed at other sites – e.g. rainfall)

The purpose for which a site has been selected for monitoring is relevant in helping to decide a course of action if a site becomes unavailable for monitoring (Section 4.2.3) and is also relevant when considering what actions would be appropriate if a Deviation is deemed to have occurred at that site (Sections 6.2.1 and 6.3.1 and 6.4).

Sites are also defined in terms of their criticality which reflects not only their purpose (as above) but also, for Pathway and Background sites, their uniqueness/replaceability. The criticality of the dataset will be judged by two considerations:

1. Whether there are any other datasets from nearby monitoring sites that have a good correlation with the dataset with missing data (see 'back up' sites identified in Table A.2). Where there are such alternative datasets that allow the behaviour of the system over the period of missing data to be reasonably estimated, the missing data will be viewed as being less critical.
2. The speed with which it is anticipated responses may occur at these sites, and in respect of Pathway sites between the quarries and the SAC, the speed at which changes in groundwater levels at those sites will translate into changes at the Kenfig SAC, based on the modelling work presented in SLR, 2014.

Critical monitoring sites are identified in Appendix A. The list of Critical Monitoring sites can be amended as part of the annual review if trends are occurring in a particular area that require particular attention.

4.1.2 Data storage

All data collected as part of the WMP will be stored digitally by the Quarry Operator in an appropriate database system with an associated digital backup system (including off site storage of backup material). Digital copies of the data will be made available to the

[5] Sites in Tables A.1 and A.4 are all Source monitoring sites, Sites in Table A.3 are all Receptor monitoring sites. In Tables A.2 sites are identified individually.

Regulator as part of the annual reporting process (Section 5.3). However, relevant digital data would also be made available to support discussion on Contingency Measures (Section 8) and/or upon reasonable written request by the Regulator.

4.1.3 Third party monitoring

Table A.5 in Appendix A summarises other hydrometric monitoring that is being carried out in the area by third parties. Much of the data collected by third parties is of use in understanding the hydrogeological processes that are occurring in the area but does not form part of the requirements of this WMP. However, some datasets currently collected by third parties are identified as being of critical value to the operation of the WMP. These are highlighted in Bold in Appendix A, Table A.5 (third party monitoring) and duplicated in Sections A.1 to A.5 (monitoring for which the Quarry Operator is responsible).

4.2 Procedures for Managing Problems with the Monitoring Network

Appendix A sets out the monitoring required under this WMP. As this monitoring will need to be carried out over many decades, it is anticipated that a range of practical problems may be encountered in the future. The section below sets out procedures that should apply when such problems are encountered. It also sets out what failings would be substantial enough to trigger Contingency Measures. The timescale for remedial actions is different for Contingency Measures (Section 8) than for the 'anticipated' problems set out in this section.

The overall objective of the procedures in this section is to ensure that the network be maintained by the Quarry Operator at an appropriate level of functionality to allow the WMP to operate effectively. This requires a balance to be struck such that the need to ensure that critical data are collected is achieved but that this does not introduce unreasonably onerous requirements on the Quarry Operator.

The monitoring requirements of the WMP may also need to be revised in future: a mechanism for identifying and agreeing the need for such changes is described in Section 5.3.

For each site in Table A.2 (which sets out the water level monitoring sites), potential 'back up sites' are listed. These are sites which have a good correlation with the listed sites and could be appropriate alternative sites if data are lost at a site or if a site becomes unavailable for monitoring.

4.2.1 Missing data

The Quarry Operator will endeavour to ensure that all the monitoring specified in Appendix A is carried out each year. However, it is accepted that, even in well operated monitoring networks, there will be occasions on which data are not collected. Possible reasons for this include:

- Temporary inaccessibility of particular sites;
- Other practical difficulties with recording data at a site; or
- Loss or corruption of data collected by data loggers.

Experience at other equivalent sites with well managed hydrometric monitoring networks at which similar numbers of data loggers are employed indicates that it should be possible to achieve 90 to 95% of the target data collection across the whole network over the course of a year. The collection rate at individual sites would typically be 100% but, at a few sites, the rate of collection may drop below this (e.g. loss of one month's data would lead to a data collection rate of 92% at that site).

Given that missing data is an expected condition, it is important to have procedures in place to deal with the situation. The following procedures will therefore apply for losses at individual sites:

- Where data are lost because of problems during a particular month (i.e. all data for one monitoring round at a particular site), this shall be recorded by the Quarry Operator and reported in the annual review of data. The Quarry Operator will make reasonable efforts to ensure that the data loss does not extend to the following month. The annual report will explain the reason for the loss and propose actions that will be taken to prevent future loss.
- If the level of monitoring coverage across the network drops below 80% in any month (e.g. no data collected at more than 20% of sites), the Quarry Operator will notify the Regulator of the situation within 10 working days of becoming aware of the data loss and will outline the measures that are being taken to rectify the situation.
- If it becomes apparent that the period of data loss at any Critical site will exceed 60 days (i.e. the problem will not be rectified by the end of the next monitoring round), the Quarry Operator will notify the Regulator of the situation within 10 working days of becoming aware of the potential data loss and will outline the measures that are being taken to rectify the situation.
- In general the Quarry Operator will aim to re start monitoring within 1 month of notifying the Regulator for Critical Sites and within 3 months for other sites.
- For the above situations, the Regulator will consider the Quarry Operator's proposals and may recommend alternative monitoring that should be carried out during the period when data continues not to be collected. Any such alternative monitoring that is recommended by the Regulator should be proportionate to the criticality of the potentially missing data for the purposes of implementing this WMP.

Where the data losses of over 60 days apply to more than three Critical sites during the same period, this will trigger Contingency Measures (see Section 8).

4.2.2 Incorrect data

The QA measures outlined in Appendix B are designed to minimise the risk that data will be incorrectly recorded. The review elements of these QA measures and the annual data review (Section 5.3) should also help to identify where data have been incorrectly recorded.

Where data are identified as being incorrect (or potentially incorrect) the Quarry Operator shall flag them as being as such in the database system. If information is available to allow the data to be corrected, this shall be carried out by the Quarry Operator. However, the Quarry Operator shall maintain a digital record of any corrections made so that any corrected data can be identified as such.

Where the QA measures indicate that incorrect data are still being collected this will be treated in the same way as for missing data (Section 4.2.1) with respect of notification of the Regulator and remedial actions/Contingency Measures.

4.2.3 Site unavailable

It is not anticipated that monitoring Receptor monitoring sites will become a problem due to lack of access (it is in the interest of the owners/controllers of Receptors for the monitoring to take place and it would not be possible to initiate Planned Mitigation Measures or Contingency Measures under this WMP unless data are available).

The majority of the Source and Pathway sites that the Quarry Operator is required to monitor (Appendix A, Sections A.1 to A.5) are either under the direct control of the Quarry Operator, within the land under the control of one of the adjacent quarries that will have related Water Management Plans (Gaens' and Grove), or on land controlled by a public body (e.g. Kenfig Pools and Dunes NNR). The remaining Pathway sites are relatively few in number. However, it is possible that, at some point in the future, one or more of the sites may become unavailable for monitoring.

If it becomes apparent that a site has become unavailable for monitoring (or permanently unsuitable for monitoring for any reason), the Quarry Operator will notify the Regulator of the situation within 21 days of becoming aware of the potential loss of the site and will outline any proposed alternatives.

The Regulator will consider the proposal being made by the Quarry Operator. The Regulator may either accept the Quarry Operator's recommendation or may recommend an alternative. Alternatives that could be considered in these circumstances are:

- Changing the monitoring frequency at an existing nearby, equivalent monitoring site (see 'back up' sites listed in Table A.2);
- Changing the monitoring requirement to an existing unmonitored site for which access would be available (Appendix D of Appendix 7.1 SLR, 2014); or
- Changing the monitoring requirement to a new site at which access would be available and at which an appropriate monitoring structure is not at the time installed. For Pathway sites, it is anticipated that any replacement sites should be within 300 m of the original site and ideally within the same geological formation.

Any alternatives that are specified should be proportionate to the criticality of the potentially missing data (see Section 4.1.1 for definition of criticality of datasets).

If the Regulator reasonably specifies that a new monitoring site needs to be introduced to the monitoring network, the Quarry Operator will use its reasonable endeavours to achieve the installation of the monitoring point within 6 months of agreement to do so. New monitoring sites will only be specified for locations at which the Quarry Operator can reasonably obtain access.

4.2.4 Cessation of third party monitoring

Natural Resources Wales has duties under various legislation (e.g. Habitats Directive, Water Framework Directive etc.) to protect and manage water related features that are of relevance to this WMP. In order to achieve this, Natural Resources Wales carries out monitoring activities in the area as listed in Appendix A (Table A.5). Bridgend County Borough Council is also responsible for monitoring at the Kenfig Dunes National Nature Reserve and there is some monitoring carried out at nearby landfill sites. Monitoring will also be required at Gaens' and Grove Quarries under their respective WMPs.

Some of the sites currently monitored by third parties have been identified as being of critical value to the operation of the Quarry WMP. These sites have been highlighted in Table A.5 and the Critical water level monitoring sites are duplicated in Sections A.1 to A.5 (monitoring for which the Quarry Operator is responsible).

If the Quarry Operator becomes aware that a third party is no longer monitoring any of the Critical sites listed in Table A.5 or that the QA methods applied by the third party at these sites are not adequate by reference to Appendix B, the Quarry Operator will notify the Regulator within 21 days that this is the case and suggest any appropriate actions.

The Regulator will consider the Quarry Operator's proposals and may recommend alternative monitoring that should be carried out by the Quarry Operator. Alternative monitoring that can be recommended in these circumstances is:

- Taking over the monitoring at the Critical third party site (subject to access agreements being obtainable);
- Moving a data logger from another, less Critical site to ensure that regular monitoring is still achieved at the third party site; or
- Changing the monitoring frequency at an existing nearby, equivalent site.

Any alternative monitoring that is specified should be proportionate to the criticality of the potentially missing data (see Section 4.1.1 for definition of criticality of datasets). In addition, no monitoring shall be recommended at sites to which the Quarry Operator does not have or cannot reasonably obtain access.

Measures that require the introduction of a new site to the monitoring network shall be dealt with under the procedures outlined in Section 4.2.3.

5 REVIEW AND REPORTING

5.1 Monthly QA

The Quarry Operator will carry out monthly QA of the data collected as described in Section B.1 of Appendix B.

5.2 Interim Report

The Quarry Operator will carry out an interim review of the data collected by the Quarry Operator and third parties during the 6 month period from November to April each year. The Quarry Operator will submit a concise interim data review report to the Regulator within 60 days of the end of the period under review (i.e. end of July each year). Achievement of this timescale will be assisted by third parties providing the data promptly.

The Interim report will assess the level of compliance of the monitoring carried out during the 6 month period and will list any problems with the monitoring and associated remedial actions.

Any sudden changes in the record at any of the sites monitored will be noted together with any steps taken to investigate further.

Any other actions triggered under the WMP (e.g. Contingency Measures) will be noted.

5.3 Annual Report

The Quarry Operator will carry out a review of the data collected by the Quarry Operator and third parties during each 12 month period from November to October. An annual data review report will be submitted by the Quarry Operator to the Regulator within 90 days of the end of the period under review (end of January). Achievement of this timescale will be assisted by third parties providing the data promptly.

The annual data review report will contain:

1. A description of any activities in the Quarry during this period that are relevant to local hydrogeological conditions. This will include presentation of data showing the rate of pumping from the quarry sump and the rate of pumping to adjacent discharge points together with plans of the Quarry showing the location of any sumps and the benches that have been worked during the period.
2. Assessment of quarry pumping rates against an appropriate Climate Based Assessment Criterion (Section 6.4.2).
3. Graphical presentation of all of the monitoring data collected at appropriate scales (e.g. for both the 12 month period and the full period of data availability).
4. Summary tables showing percentage completeness of data collection relative to target (as set out in Appendix A) together with a description of any difficulties encountered in collecting the data.
5. A concise summary of any incorrect or missing data that have been identified and how they have been treated.
6. Summary tables showing the range of values measured at each site during the 12 month period and how this compares to previous periods.
7. A summary of the condition of each monitoring point including comment on any possible change in datum levels and the recent plumbed depth of each borehole/dip well.
8. A concise summary of climatic conditions during the 12 month period and how this compares to previous periods.
9. A summary of any indications in the data that the conceptual model of the local hydrogeology as set out in SLR, 2014 (or as subsequently modified in previous annual

reports) needs to be adjusted and the significance of any such adjustments for the conclusions of the ES and hence the requirements of the WMP.

10. A comparison of the data collected at each site against the relevant Assessment Criteria for the 12 month period under review (see Section 6.2.1 and 6.3.1). This should also include an assessment of any observed trends and Deviations and thus the likelihood of a Significant Deviation occurring in the following review period.
11. An assessment of the significance of any Deviation (see Section 6.4). Note that exceedance of an Assessment Criterion by Quarry pumping rates (Section 6.4.2) automatically triggers changes to Planned Mitigation and/or Contingency Measures (Section 8) i.e. the Deviation mechanism does not need to be applied to achieve changes in Planned Mitigation Measures.
12. An assessment of the effects of any changes that have been made to the way in which the quarry discharges water over the previous 12 month period.
13. A description of any Contingency Measures (Section 8) that have been required during the previous 12 month period.
14. Recommendations for changes required to the monitoring network in order to support achievement of the objective of the WMP.
15. Recommendations for any changes in the Trigger levels or CBACs to take into account the data collected in the period under review[6].
16. Recommendations for any adjustments to the Planned Mitigation Measures (Section 7) being carried out supported as necessary by Appropriate Calculations (Section 6.7) to demonstrate that this will achieve the desired objective (either to reverse a Significant Deviation that has occurred or to forestall a Significant Deviation that seems likely (on the basis of observed trends) to occur in the coming period).
17. Recommended changes to the monitoring system to allow the effectiveness of any such changes to be monitored. During the Recovery Phase (Section 3.2), it is anticipated that this will include an assessment of how much residual pumping will be required to minimise any adverse environmental impacts.
18. An outline of any proposed developments that are scheduled to take place in the Quarry over the coming 12 months that have a bearing on the local hydrogeology (e.g. construction of new sumps, working of new benches, changes to pumping regime etc.) together with an assessment of likely effect on dewatering rates (i.e. a guide to likely dewatering rates under different rainfall scenarios).
19. A digital copy of all data collected during the course of the previous 12 months.

Copies of any reports issued will be sent direct to the relevant offices/departments of the Regulator and the statutory consultee (Natural Resources Wales).

5.4 Overview by the Regulator

The Regulator will review the Interim and Annual Reports in detail and will write to the Quarry Operator within 90 days of receiving the report detailing:

- Confirmation (or not) that the monitoring has been carried out as required;
- Confirmation (or not) that the Assessment Criteria had been correctly applied;
- Acceptance or disagreement with the conclusions reached;
- Acceptance or disagreement with the recommendations made;

[6] For clarity, changes CBAC threshold ranges will be considered during annual review but the Sensitivity Criteria used to determine that a Deviation is significant would only be reviewed as part of future ROMP cycles..

- Details of any recommendations that the Regulator requires for changes in the WMP, including a need for a change to the periodicity of review.

In the absence of any comment within the 90 day period, the Regulator will be deemed to have accepted the content, findings and recommendations of the Annual Report.

Note that, due to the subtle and gradual nature of some of the changes that may occur, it is possible that the start of a Deviation may only become apparent several years later. Therefore confirmation that no Deviations have been detected in one year does not mean that a future assessment (with the benefit of additional data) may not conclude that the Deviations started at that point. The timing of any actions required following a Significant Deviation will be measured from the date of the Annual Report reporting of the Significant Deviation. In the event that the Significant Deviation is found to have started in a previous interim or Annual Reports, the Quarry Operator and Regulator will use reasonable and proportionate endeavours to expedite actions required.

6 MECHANISM FOR DETERMINING WHETHER A DEVIATION HAS OCCURRED AND IDENTIFYING RESULTANT ACTIONS

6.1 Summary of Approach

The general approach to assessing the data collected under the WMP is that, as part of the Interim or Annual Report process, data at each monitoring site are assessed against an Assessment Criterion (either a Trigger Level (Section 6.2) or a Climate Based Assessment Criterion (Section 6.3) as set out for each site in Appendix D2).

Where the data are considered to have 'exceeded' an Assessment Criterion (details of how 'exceedance' is defined are discussed in relevant sections below), a Deviation is considered to have occurred. Deviations at Pathway and Receptor sites which exceed a pre-defined Sensitivity Criterion are to be considered and if they are Significant Deviations as set out in Section 6.4 certain actions are required to be taken (Section 6.6)[7].

Figure 1 illustrates the sequence of events in the procedure for determining whether a Deviation from an Assessment Criterion has occurred and whether any changes to the Planned Mitigation Measures are required as a result. In summary, the following steps are required:

1. Compare the measured data at the monitoring site against the relevant Assessment Criterion (Appendix C);
2. If a Deviation is identified (Sections 6.2.1 or 6.3.1), assess whether that Deviation is a Significant Deviation (Section 6.4);
3. Review the spatial pattern of Deviations, the behaviour of the groundwater system during the period in question (Section **Error! Reference source not found.**) and carry out Appropriate Calculations (Section 6.7) to determine whether dewatering activities at the Quarry are a contributory cause to any Significant Deviations;
4. If dewatering activities at the Quarry are a contributory cause to any Significant Deviations, identify any amendments required to the Planned Mitigation Measures (Sections 6.6 and 7) and monitoring under the WMP[8].

Two different types of Assessment Criteria are used in this WMP: Trigger Levels (Section 6.2.1) and Climate Based Assessment Criteria (Section 6.3.1). Different procedures apply to these different approaches as described below. Sites using each type of criterion are listed in Appendix C. In general, Climate Based Assessment Criteria are used for sites with good monitoring records which show predictable responses to antecedent rainfall, whereas Trigger Levels are used for sites with shorter data periods or irregular responses to rainfall. It is anticipated that as the data sets for the monitoring sites improve, there will be a gradual migration of some of the remaining sites with Trigger Levels to Climate Based Assessment Criteria. Steps required to achieve this migration are described in Section 6.7.

[7] NB The process for annual reporting (Section 5.3) also requires a review of trends and deviations to assess whether a Significant Deviation is likely to occur in the next reporting period.

[8] See paragraph 6.5 3.d as to what should happen in circumstances where dewatering operations cannot be ruled out as a potential contributory cause.

6.2 Trigger Levels

6.2.1 Definitions

Trigger Levels are absolute values against which data can be compared. If any of the data measured at a Pathway or Receptor site[9] 'exceed'[10] the relevant Trigger Level, a Deviation has occurred. The proportion of the data in the period under review that has to 'exceed' the Trigger Level before a Deviation is considered to have occurred is defined in Section 6.2.2.

Trigger Levels are a relatively simple approach to setting Assessment Criteria and suffer from a limited ability to take into account antecedent climatic conditions which usually dominate the data being recorded. However, there are some sites for which Climate Based Assessment Criteria are not appropriate: this principally applies to shallow ponds and wells (e.g. ID 17, 20, 23 etc. in Table A.2) or sites affected by tidal variations (e.g. ID 21 in Table A.2). Trigger Levels have been developed for these sites, as set out in Appendix C.

Some other sites (e.g. HL 6, 11, 13, 14 and 15) have no Trigger Levels because there is currently insufficient data to develop a Climate Based Assessment Criterion. Transitional arrangements for developing new Trigger Levels or moving from Trigger Levels to Climate Based Assessment Criteria at these sites are set out in Section 6.8 and Appendix C.

6.2.2 Proportion of data to 'exceed' a Trigger Level Assessment Criterion before a Deviation is considered to have occurred

Data derived from the monitoring of natural systems typically have a degree of 'noise' in them. The aim of this section is to define periods over which data have to 'exceed' a relevant Trigger Level Assessment Criterion before a Deviation is considered to have occurred, so that the effects of such 'noise' in the data do not unnecessarily affect the water management at the Quarry.

Where a pre-defined proportion of the data measured at a Pathway or Receptor Site 'exceed' a relevant Trigger Level Assessment Criterion by a defined amount during the period under review, it will be considered that a Deviation has occurred[11].

The relevant proportions of the data are defined as follows:

- For a water level monitoring site monitored by a data logger at daily intervals (or more frequently), the proportion is 10% of values measured during the 12 month period under review.
- For a water level monitoring site monitored manually at monthly intervals, the proportion is two consecutive values measured during the 12 month period under review.

Similar proportions will be derived for stream and spring flow data series once a representative period of time series data has been collected (See Section 6.7).

The amount by which the data measured at a Pathway or Receptor Site need to 'exceed' a relevant Trigger Level Assessment Criterion to contribute to a Significant Deviation is set out in Section 6.4.

If it appears, by reference to a Trigger Level, that a Significant Deviation has occurred, it may be appropriate to develop a Climate Based Assessment Criterion for that site to confirm this conclusion. However, this should not delay the issue of an Annual Report or the conclusion as to whether a Significant Deviation has occurred at that site.

[9] Deviation can only be defined for Pathway and Receptor monitoring sites. Source water level monitoring sites are by definition already significantly affected by Quarry dewatering. Exceedance of an Assessment Criterion by Quarry pumping rates triggers Contingency Measures (Section 8).
[10] Note, trigger levels may either be minimum values or maximum values. In the former case, 'exceed' in this context means to fall below, in the latter case, to fall above.
[11] Note that the loss of water supply from a private water supply that has been identified in the Quarry ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at the Quarry triggers Contingency Measures (Section 8).

6.3 Climate Based Assessment Criteria

6.3.1 Definitions

A Climate Based Assessment Criterion is a calculation that allows the ‘natural’ behaviour of a monitoring site under different climatic conditions to be estimated. The approach that is used to calculate these Climate Based Assessment Criteria is outlined in Appendix D. By making allowance for antecedent climatic conditions, the Climate Based Assessment Criteria allow a more sensitive assessment of other effects on the local groundwater system (e.g. quarry dewatering) to be carried out.

Deviation from a Climate Based Assessment Criterion is defined as the occurrence of a statistically significant difference between the behaviour measured at a Pathway or Receptor Site[12] and the behaviour predicted by the relevant Climate Based Assessment Criterion. The statistical approaches that will be used to determine the presence and size of any Deviation between the observed data and the Climate Based Assessment Criteria are described in Appendix D.

The Climate Based Assessment Criterion for a site needs to be calibrated against a ‘baseline’ - observed data from that site for a period over which it can be agreed that there are no significant effects of water management at the Quarry on the observed data (or if there are such effects, that correction can be made for them). The CBACs that have been developed for various flow and water level monitoring sites are presented in Appendix C.

6.3.2 Determination that a Deviation has occurred

As with all models of natural systems, there will be some variance between the simulated and observed values. The size of this variance will determine both the confidence that can be placed in the Climate Based Assessment Criterion for that site and also the minimum difference between the simulated and observed data that could be considered to be statistically significant.

For each of the Climate Based Assessment Criteria set out in Appendix C, threshold ranges have been set, based on the range of CuSum trends that have occurred in the baseline period. If these threshold ranges are exceeded, further statistical tests should be carried out as described in Appendix D, to check whether there is a statistically significant difference between modelled and observed data in the periods before and after the CuSum trend started. If there is such a statistical difference, it will be concluded that a Deviation has occurred at that site.

6.4 Assessment of the Significance of a Deviation

6.4.1 Receptor Sites

Where a Deviation has been determined at a Receptor Site, the Quarry Operator will assess the significance of the Deviation by reference to the sensitivity of that Receptor. The following Sensitivity Criteria will be used for determining whether a Deviation at a Receptor site is a Significant Deviation[13].

- For licensed groundwater abstraction boreholes, a groundwater level reduction in excess of 0.5 m relative to the relevant Assessment Criterion is taken to indicate a potentially significant impact unless further assessment (i.e. evaluation of borehole construction details, pump intake level etc.) indicates that this has not materially affected the functioning of the supply.

[12] Deviation can only be defined for Pathway and Receptor monitoring sites. Source water level monitoring sites are by definition already significantly affected by Quarry dewatering. Exceedance of an Assessment Criterion by Quarry pumping rates triggers Contingency Measures (Section 8).

[13] Note that the loss of water supply from a private water supply that has been identified in the Quarry ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at the Quarry triggers Contingency Measures (Section 8). It is anticipated that this would be identified by the owner reporting the loss to the Operator.

- For shallow wells, a groundwater level reduction in excess of 0.25 m relative to the relevant Assessment Criterion is taken to indicate a potentially significant impact unless further assessment indicates that this has not materially affected the use or value of the well[8].
- For ponds (excluding Kenfig Pool and any dune slacks in Kenfig Pool and Dunes and Merthyr Mawr SAC) the criteria will be a change of 0.1 m relative to the relevant Assessment Criterion for each of the ponds monitored (sites 17, 20 and 23 in Appendix A, Table A.2) unless further assessment indicates that this has not materially affected the use or amenity/ecological value of the pond.
- For spring flows, a reduction of flow in excess of 10% of mean long term flows relative to the relevant Assessment Criterion is taken to indicate a potentially significant impact unless further assessment indicates that this has not materially affected the use or value of the spring.

The Environmental Statement showed that the proposed future development of the quarry would not have an adverse environmental effect on Kenfig SAC provided that Planned Mitigation Measures (Section 7) are carried out as set out in this WMP. However, notwithstanding that conclusion, the possibility remains that conditions may differ from those assessed. The hydrological sensitivity criterion for the SAC agreed with NRW for the purposes of assessing impact on the integrity on the Kenfig SAC is set out in the preface to this document but is not included as a Sensitivity Criterion within the WMP as the WMP seeks to prevent adverse impacts on the Kenfig SAC from occurring by reference to intermediate Pathway Sites, where potential impacts on groundwater levels can be detected early, before they translate into an impact at the Kenfig SAC receptors, with sufficient time for remedial action to be taken via changes to Planned Mitigation/Contingency Measures. However, the monitoring of the Kenfig SAC receptors still fulfils an important function in that the conceptual modelling carried out and the efficacy of mitigation strategies can be checked.

6.4.2 Pathway Sites

The modelling carried out for the ES for the Quarry (SLR, 2014) indicates that some changes are anticipated at Pathway sites. The occurrence of a change in water levels at a Pathway site below the precautionary Sensitivity Criteria set out below may indicate the effect of natural variations in ground water levels or the application of different Planned Mitigation Measures but, on their own, should not be taken as a cause for concern.

The occurrence of changes in water level that are equal to or exceed those Sensitivity Criterion set out below will be taken that a risk that an impact could occur after a period of time at the Kenfig dunes SAC and will suggest that some elements of the conceptual model and Planned Mitigation Measures and or Contingency Measures need to be revisedThe minmum and maximum time delay between the breach of a Sensitivity Criteria and the impact on the integrity of the SAC is set out below for reference purposes.

The Sensitivity Criteria for the various Pathway Sites are as follows:

Sensitivity Criteria For Pathway Sites

Site	Receptor	Estimated water level change at Pathway site for 0.1m at Kenfig/Merthyr Mawr (m)*	Sensitivity. Criterion (m)	Min delay from pathway response to response in SAC (years)	Max delay from pathway response to response in SAC (years)
21	Merthyr Mawr	1.2	1	3.1	4.8

40	Kenfig	33.6	7.5	8.0	10.3
A-a	Kenfig	2.1	0.75	7.7	9.4
B-a	Kenfig	3.3	1	7.8	9.9
C (new)	Kenfig		1.5	7.9	10.4
D (new)	Kenfig		5	8.0	10.3
G	Merthyr Mawr	8.0	3	3.1	4.3
H	Merthyr Mawr	1.2	1	3.1	4.8
K1a	Kenfig	0.3	0.1	7.4	8.6
K2a	Kenfig	0.3	0.1	7.4	8.6
N (3)	Kenfig	0.7	0.25	7.6	8.7
O	Kenfig		0.5	4.4	9.6
P	Kenfig		5	6.2	10.0
Q	Kenfig		7.5	7.4	9.3
R	Kenfig		0.5	4.4	9.6
T	Merthyr Mawr	2.3	1	3.1	4.2
T_95/01	Merthyr Mawr	30.0	7.5	3.5	4.7

Cells shaded grey are not on direct pathway to stated receptor.

These values were derived by interrogating the outputs from the scenario runs of the transient water balance (ES Appendix 7.4) to compare the change in water level at each model cell with the maximum response at the SAC on that pathway. These pathway responses were then scaled up to be equivalent to a 0.1 m change at the SAC assuming a direct proportionality between the two. The mean value for the different scnearios is presented here. Note that if the simulated change in water level at the SAC was in a different direction to that in the Pathway site, then this result will be negative (i.e. those sites are probably not appropriate for the purpose of detecting and preventing water level change at the SAC – these values have not been included in the table above and mostly occur at sites that are not on a direct pathway to the SAC).

6.4.3 Quarry pumping rate

The Scoping Direction requires assessment of:

> *the potential impact of quarrying on hydrology and hydrogeology of the area, including the possibility of interception during quarrying of a 'highly permeable feature' within the limestone, and although there is a low probability of this occurring the prospect should be recognised as a continuing risk during further development of the quarry and appropriate action identified (for example a risk management/ monitoring strategy which recognises the critical stage at which potential adverse impact may occur);*

Discussion with Natural Resources Wales has indicated that an appropriate way of managing this risk is to focus on regularly determining whether the pumping rate in the quarry is in the range anticipated.

A Climate Based Assessment Criterion for pumping rates at the quarry (ref Section 6.4.2) will be included in Appendix C in future to allow the regulator to check whether pumping rates are higher than anticipated. There is currently only intermittent dewatering with Gaens' Quarry and no data associated with this. It is therefore not feasible to develop a Climate Based Assessment Criterion for the Quarry. The Quarry operator will implement an enhanced monitoring scheme within the quarry by 31 March 2016 and, once a sufficient amount of data from these additional components becomes available, the preliminary Climate Based Assessment Criterion will be developed and finalised.

6.5 Identification of the Cause of Deviations and Significant Deviations

As part of the annual report (Section 5.3), the Quarry Operator will review the spatial distribution of any Deviations and/or Significant Deviations (collectively “deviations” in the text below) that have been identified in the 12 month period under review with the aim of identifying their cause. In addition, the Quarry Operator will also review the available monitoring data and assess whether it is likely that any deviations are likely to occur in the next 12 month period.

If any deviations have occurred or are considered likely to occur, three possible outcomes of this review are anticipated:

1. The pattern of deviations clearly indicates that water management at the Quarry is a contributory cause of the deviations. In this circumstance, the Quarry Operator will identify appropriate changes to the Planned Mitigation Measures as described in Sections 6.6 and 7.
2. The pattern of Deviations clearly indicates that water management at the Quarry is not a contributory cause of the Deviations. In this case, the Quarry Operator will report this finding to the Regulator for its attention and no further action is required under Section 6.6 below. The Regulator will review this conclusion as part of its review of the annual report (Section 5.4). If the Regulator does not agree with this conclusion, it will set out its reasons for disagreeing and/or make a reasonable request further information or Appropriate Calculations that, in its view, will help to determine the cause of the Deviations.
3. The pattern of Deviations does not clearly indicate whether water management at the Quarry is a contributory cause of the Deviations. In this case, the Quarry Operator will carry out Appropriate Calculations (Section 6.6) to determine the most probable degree to which dewatering at the Quarry is the cause of the Deviations.
    a. If the Appropriate Calculations indicate that water management at any of the Cornelly Group of Quarries is not a contributory cause of the Deviations, the Quarry Operator will report this finding to the Regulator for its attention.
    b. If the Appropriate Calculations indicate that water management at another of the Cornelly Group of Quarries is a contributory cause of the Deviations, the Quarry Operator will report this finding to the regulator and the relevant Quarry Operator for implementation via the relevant WMP.
    c. If the Appropriate Calculations indicate that water management at the Quarry is a contributory cause of the Deviations, the Quarry Operator will identify appropriate changes to the Planned Mitigation Measures as described in Section 6.6.
    d. If the Appropriate Calculations cannot rule out that water management at the Quarry is a contributory cause of the Deviations, the Quarry Operator will need to identify and implement changes to the Planned Mitigation Measures described in Section 6.6 on a precautionary basis until such time that water management at the Quarry can be ruled out as a cause.

If the scale and extent of Deviations is significantly different from that anticipated in the ES (SLR, 2014 as summarised Appendix F), then this would trigger Contingency Measures (Section 8).

6.6 Identifying Actions Required in the Case of a Significant Deviation Occurring at a Receptor Monitoring Site

Where a Significant Deviation has been identified, as part of the annual report, the Quarry Operator will recommend adjustments to the Planned Mitigation Measures/Contingency

Measures (Section 7 and 8)[14]. These adjustments should be proportionate to the degree to which the Quarry is a contributory cause of the Significant Deviation. The Quarry Operator will support its proposal for adjustments to the Planned Mitigation Measures/Contingency Measures by means of Appropriate Calculations (Section 6.7) as necessary.

6.7 Appropriate Calculations

Some parts of the WMP require Appropriate Calculations to be carried out. For instance:

- Calculations to develop Climate Based Assessment Criteria (Section 6.3).
- Calculations required to clarify the extent to which dewatering at the Quarry is the cause of a Deviation (Section 6.3);
- Calculations to assess whether a Deviation is likely to occur at a Receptor monitoring site in the next 12 months (Section 6.5); and
- Calculations to demonstrate the likely effectiveness of proposed adjustments to Planned Mitigation Measures (Section 6.6).

Appropriate calculations can include some or all of the following:

- Simple scoping calculations using appropriate analytical and mass balance equations
- Time series recharge calculations such as those presented in Appendix D;
- More complex calculations such as the Flow Network Model presented in Appendix 7.3 of SLR, 2014 (included as Appendix E of this document for completeness);
- Distributed numerical groundwater modelling of all or parts of the system.

The complexity of the calculations applied will be discussed and agreed with the Regulator (and the relevant statutory consultees) and will be proportionate to the significance of the impacts being considered and the actions required as a result of the calculations.

6.8 Current Status and Future Development of Assessment Criteria

Sites for which Assessment Criteria are required are the Pathway and Receptor sites listed in Table A.2 in Appendix A and all the sites in Table A.3 in Appendix A. These should be CBACs except where these are considered to be infeasible (Section 6.2.1).

The current status of the various Assessment Criteria is set out for all sites in Tables C.1 (Trigger Levels) and C.2 (CBACs) in Appendix C.

Where no (or very limited) data are currently available for a site, Table C.3 sets out which alternative sites should be considered to represent conditions at the site until an adequate data set is available to define a Trigger Level or CBAC.

[14] Note that the loss of water supply from a private water supply that has been identified in the Quarry ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at the Quarry triggers Contingency Measures (Section 8).

7 PLANNED MITIGATION MEASURES

7.1 Available Planned Mitigation Measures

The Planned Mitigation Measures for water management at the Quarry available under the terms of this WMP are:

1. Pumping to a northern quarry sump

No other sites for Planned Mitigation Measures for water management at the Quarry are currently available to the Quarry Operator. However, the ES (SLR, 2014) showed that these measures would be adequate for mitigating any small effects on the local hydrological system. Where a Significant Deviation has been identified, as a part of the annual or interim report, changes to the Planned Mitigation Measures or implementation of Contingency Measures may be proposed by the Quarry Operator in the relevant report and or required by the Regulator. Changes or alternatives to the Planned Mitigation Measures referred to above may include alternative re-injection locations to those currently available, or other measures that are considered to be necessary to ensure there is no ongoing breach of the Sensitivity Criterion and no impact on the Kenfig Dunes SAC. Any such changes to the Planned Mitigation Measures will need to be incorporated into later versions of the WMP (see also Contingency Measures Section 8).

In the case of a Significant Deviation occurring at a private water supply (as listed in Appendix A, Table A.2) [15], Planned Mitigation Measures may also include:

2. Modification to the structure of the private water supply to minimise or remove the impact (e.g. deepening a well or borehole or lowering the pump);
3. Provision of an alternative mains water supply; or
4. Financial compensation for the loss of the water supply.

In the event of a quarry off-site discharge failing to meet the terms of the relevant Environmental Permit, Planned Mitigation Measures include dilution within the large volumes of water held in various quarries and simple options for treatment such as aeration etc.

7.2 Implementation of Planned Mitigation Measures

The Quarry Operator will make reasonable endeavours to implement any recommended adjustments to the Planned Mitigation Measures within 6 months of agreement of the measures.

If the Deviation is large enough to cause the interruption of water supply at a private water source that has been identified in the Gaens' ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at Gaens' quarry (this triggers Contingency Measures), then the Quarry Operator will respond within 5 working days (Section 8).

As part of the implementation of the Planned Mitigation Measures, the Quarry Operator will submit details of any adjustments to the monitoring programme in Appendix A that are required in order to determine the effectiveness of the revised Planned Mitigation Measures (See Point 15 in Section 5.3).

[15] Note that the loss of water supply from a private water supply that has been identified in the Quarry ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at the Quarry triggers Contingency Measures (Section 8).

8 CONTINGENCY MEASURES

Contingency Measures are actions that may be required under the WMP in circumstances where events occur that were not predicted in the ES or in the previous annual report and that require actions to be carried out before the next 12 month data review is complete (excluding the generally anticipated difficulties with any monitoring network defined in Section 4.2).

The following events will trigger Contingency Measures:

- An increase of the monthly quarry pumping rate so that it exceeds the maximum rates predicted in the relevant Climate Based Assessment Criterion by more than an agreed percentage (see Section 6.4.3);
- Occurrence of any signs of significant ground instability in and around the Quarry that could reasonably be attributed to activities in the Quarry;
- The loss of monitoring data at more than three Critical sites in a particular month due to the same cause;
- The loss of more than 60 days monitoring data at more than three Critical sites in a 12 month period;
- The loss of water supply from a private water supply that has been identified in the Quarry ES (SLR, 2014) as being potentially vulnerable to changes in water management activity at the Quarry[16];
- The scale and extent of Deviations observed during a 12 month period is significantly different from that anticipated in the ES (SLR, 2014 as summarised Appendix F);
- A marked change in the behaviour of a Pathway or Receptor monitoring site relative to previous behaviour at that site such that it is reasonable to expect that a Significant Deviation has occurred.

Other events in the Quarry that can reasonably be considered by the Quarry Operator or Regulator to be likely to affect the local groundwater systems rapidly in ways that were not anticipated at the time of the issue of the previous annual report will also trigger Contingency Measures.

The Quarry Operator will notify the Regulator of the occurrence of such an event within five working days of becoming aware of its occurrence. Within 21 days of notifying the Regulator of the occurrence of such an event, the Quarry Operator will inform the Regulator of the steps which it intends to take in response to an event, with, where appropriate, a list of proposed Contingency Measures, and a timetable for implementing those measures.

In the case of loss of water supply from a private water supply, the Quarry Operator will investigate the reason for the loss of supply and, if it is attributable to water management activities in the Quarry, will make arrangements to provide an alternative or back up supply within five working days as a short term measure. After this, the normal Contingency Measures procedure will apply.

Contingency Measures may include:

- Additional monitoring of water levels, pumping rates or water quality;
- Changes to the way water is managed within the Quarry (see Sections 3 and 7.1);
- Other physical measures to minimise the problems encountered. This could include alternative re- injection locations to those currently available, as set out in Section 7

[16] It is anticipated that this loss of supply would be identified by the owner reporting it to the Operator.

above, or other measures that are considered to be necessary to ensure there is no ongoing breach of the Sensitivity Criterion and no impact on the Kenfig Dunes SAC. It could also include the type of measures envisaged in outline in Appendix G, albeit the circumstances pertaining at the time will need to be considered before the remedial action required is determined either by the Quarry Operator with the agreement of the Regulator or, in the absence of agreement, requested by the Regulator..

The Quarry Operator will also provide the Regulator with a digital copy of any data from the hydrometric network described in Appendix A that may be required by the Regulator in relation to the proposed Contingency Measures.

9 REFERENCES

SLR, 2014. Environmental Statement Volume 1 Environment Act Romp Review: Gaens' Quarry

WynThomasGordonLewis, 2004. Environment Act 1995: Review of Mineral Planning Permissions Cornelly Quarry Environmental Impact Assessment

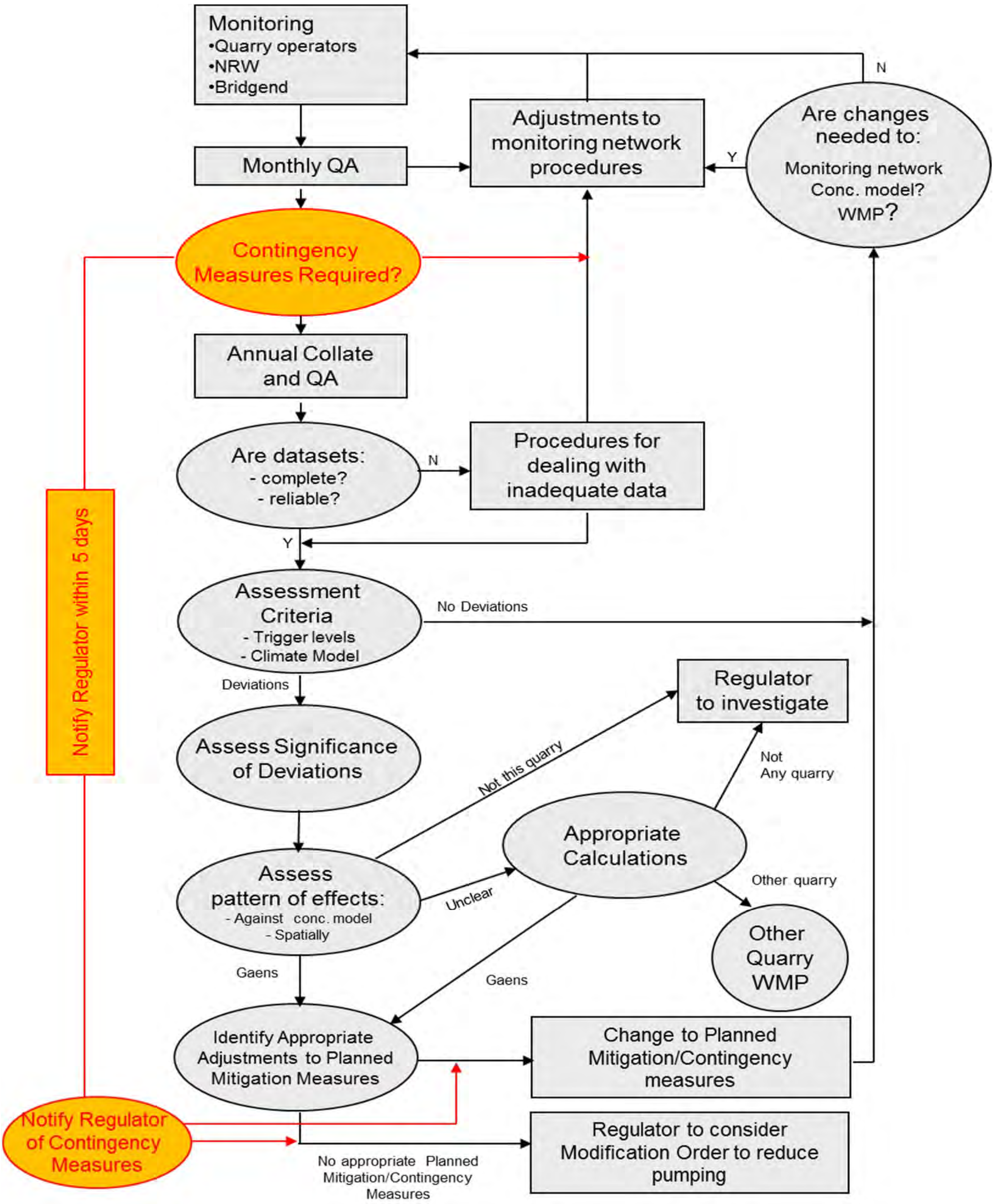

Figure 1
Illustrative flow chart showing processes required for GaensQuarry WMP

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File Reference O:\6227_Cornelly\reports\R17 EIA\Outline flow chart.xls	

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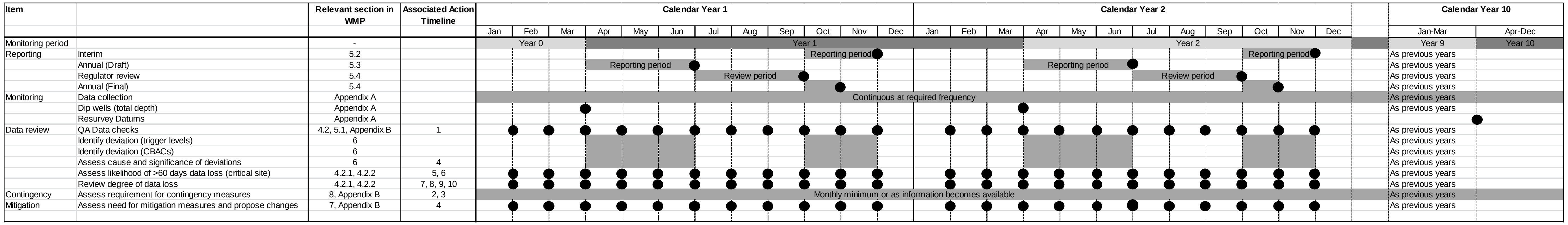
General Timelines:



Specific Event Timelines:

Ref	Event	Response time (initial)	Initial Action	Response time (follow on action 1)	Follow on action 1	Response time (follow on action 2)	Follow on action 2
1	Site unavailable/unsuitable for monitoring	21 days	Notify regulator and propose appropriate actions	Unspecified	Receive regulator feedback	+6 months	Install new site (if required)
2	Interruption to water supply	5 working days	Implementation of corrective measures				
3	Contingency measure trigger	5 working days	Notify regulator	+21 days	Present plan to regulator	As agreed	provide digital data
4	Significant Deviation identified and changes to mitigation measures required	6 months	Implementation of changes				
5	Likelihood of greater than 60 days data loss at a critical site	10 working days	Notify regulator with plans for addressing				
6	Likelihood of greater than 60 days data loss at four or more critical sites	Immediate	Initiate contingency measures				
7	Monitoring coverage drops below 80% in any month	10 working days	Notify regulator with plans for addressing				
8	Minor data loss (i.e. data loss not falling into other event categories listed here)	next annual report	Explain reason for loss and actions to prevent future loss				
9	Interruption to monitoring at any critical site	1 month	Resume monitoring				
10	Interruption to monitoring at any non-critical site	3 months	Resume monitoring				

Figure 2
Timelines

Date Apr 15	Drawn BCH
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Environment Specialists

APPENDICES

Appendix A Monitoring Requirements

A.1 Pumping Rates

The Quarry Operator will record the reading on the impellor flow meters installed on the various pumps in the Quarry on a weekly basis. The number of pumps being used will depend on the precise water management activities in the Quarry at the time. However, the Quarry Operator should measure the following flows if pumping has occurred to that site in the previous weekly period.

Table A.1 Abstraction Rate Monitoring (Source)

Site	Comment
Pumping from quarry sump	

A.2 Water Levels

The Quarry Operator will monitor water levels at the sites and frequencies set out in Table A.2. Locations of these sites are shown on Figure A.1. Decisions on monitoring frequency etc have been in part based on the speed of response indicated by the modelling carried out for the ES (SLR, 2015). Sites have been divided into Response Groups (1 is most rapid and 4 least rapid)

Two specific circumstances are noted here under which monitoring frequency would change:

1. Following 12 months of monitoring and if no response is seen in the corresponding pathway sites, monitoring at some distant receptor sites may be discontinued (subject to agreement by the Regulator). These sites are identified in the comments in Table A.2.
2. Where a Significant Deviation occurs in a Response Group 1 site, the frequency of monitoring in Response Group 2 sites on that pathway should be increased.

In either case, this would be agreed via the annual report process.

Table A.2 Water Level Monitoring (Source, Pathway & Receptor Sites)

ID	Desc. (Name)	Locality	Monitored Aquifer / Water Body	Source[1]	Receptor[1]	Pathway[1]	Receptor Group	Pathway for receptors	Alt receptor sites	Alt pathway sites	Response Group[2]	Mon frequency	Mon Method	Critical[1,3]	Land controlled by	Comment	WMP[5]
14	Borehole	Royal Porthcawl Golf Club	Triassic				Triassic West	n/a	18b, 36A, 36B		2	Monthly	Manual		Golf course		GA
17a	Pond	Ty Tanglwyst Farm, South Cornelly	Surface water (Lst)				Ty Tanglwyst Group Lst	17b, K2b, KP, K1b, CC_5, CC_9, K4	17b	D (new)	1	Monthly	Manual		Private		CO, GR
17b	Borehole	Ty Tanglwyst Farm, South Cornelly	Limestone				Ty Tanglwyst Group Lst	17a, K2b, KP, K1b, CC_5, CC_9, K4	17a	D (new)	1	Monthly	Manual		Private		CO, GR
20	Pond	The Wildnerness , Porthcawl	Surface water (Lst)				Porthcawl Group Lst	None		n/a	2	Monthly	Manual		Bridgend CBC		CO, GR
21	Borehole	White Wheat, Porthcawl	Triassic				Porthcawl Group Lst	20, 23	23	H	2	Monthly	Manual		Private	Private water supply. Tidal fluctuations.	CO, GR
23	Pond	Pwll y Waun, Porthcawl	Surface Water (Triassic)				Porthcawl Group Lst	None	21	n/a	2	Monthly	Manual		Bridgend CBC		CO, GR
34	Pond	Tythegston	Surface water (Lst)				Tythegston Group Lst	61, D4, D7, D8	61	T, G, L	3	Monthly	Manual		Private		CO
36A	Borehole	Royal Porthcawl Golf Club	Triassic				Triassic West	n/a	14, 18b		2	Monthly	Manual		Golf course		GA
36B	Borehole	Royal Porthcawl Golf Club	Triassic				Triassic West	n/a	14, 18b		2	Monthly	Manual		Golf course		GA
40	Borehole	Grove Golf Club	Triassic/Limestone				Triassic West	14, 18b, 36A, 36B			1	Daily	Auto		Golf course		GA

ID	Desc. (Name)	Locality	Monitored Aquifer / Water Body	Source[1]	Receptor[1]	Pathway[1]	Receptor Group	Pathway for receptors	Alt receptor sites	Alt pathway sites	Response Group[2]	Mon frequency	Mon Method	Critical[1,3]	Land controlled by	Comment	WMP[5]
A-a	Borehole	Kenfig	Triassic				n/a	K2b, KP, K1b, CC_5, CC_9, K4		17a, 17b, D (new), C (new), B-a, N (piezo 3), A-b, K2a	2	Monthly	Manual		Golf course		CO, GR
A-b	Borehole	Kenfig	Sand and Gravel				n/a	K2b, KP, K1b, CC_5, CC_9, K4		17a, 17b, D (new), C (new), B-a, A-a, N (piezo 3), K2a	3	Monthly	Manual		Golf course		CO, GR
B-a	Borehole	Kenfig	Triassic				n/a	K2b, KP, K1b, CC_5, CC_9, K4		17a, 17b, D (new), C (new), A-a, N (piezo 3), A-b, K2a	2	Monthly	Manual		Golf course		CO, GR
C (new)	Borehole	South Cornelly	Limestone				n/a	K2b, KP, K1b, CC_5, CC_9, K4, New Mill Farm Springs		D (new)	2	Daily	Auto		Golf course	Replacement bh	CO, GR
CC_5[4]	Borehole	Kenfig	Dune Sand				Kenfig	n/a	CC_9, K1b, K2b, KP	n/a	4	Monthly	Manual		Kenfig Corp	Apex of groundwater 'dome' in dune slacks	CO, GR
CC_9[4]	Borehole	Kenfig	Dune Sand				Kenfig	None	CC_5, K1b, K2b, KP	n/a	4	Monthly	Manual		Kenfig Corp	Western side of groundwater 'dome' in dune slacks.	CO, GR
CS	Sump (Cornelly Sump)	Cornelly	Limestone				n/a	n/a	n/a	n/a	1	Daily	Auto		Tarmac		CO, GR

ID	Desc. (Name)	Locality	Monitored Aquifer / Water Body	Source[1]	Receptor[1]	Pathway[1]	Receptor Group	Pathway for receptors	Alt receptor sites	Alt pathway sites	Response Group[2]	Mon frequency	Mon Method	Critical[1,3]	Land controlled by	Comment	WMP[5]
D (new)	Borehole	Ty Tanglwyst Farm, South Cornelly	Limestone				n/a	17a, 17b, K2b, KP, K1b, CC_5, CC_9, K4, New Mill Farm Springs		None	1	Daily	Auto		Rees & son	Replacement bh	CO, GR
E	Borehole		Limestone				n/a				1	Monthly	Manual		Tarmac		
GRS[4]	Sump (Grove Sump)	Grove Quarry	Surface water (Lst)				n/a	None (mitigation measures)		n/a	1	Daily	Auto		Tarmac		CO, GR
GAS[4]	Sump (Gaens Sump)	Gaens Quarry	Surface water (Lst)				n/a	None (mitigation measures)		n/a	1	Daily	Auto		Rees & son		CO, GR
H	Borehole	T'yn-y-caeau	Limestone				n/a	20, 21, 23		21	2	Daily	Auto		Private		CO, GR
K1a	Borehole	Kenfig	Sand and Gravel				n/a	K1b, CC_5, CC_9, K4		B-a, A-a, N (piezo 3), KP, A-b, K2a, K2b	3	Monthly	Manual		Kenfig Corp		CO, GR
K1b	Borehole	Kenfig	Dune Sand				Kenfig	CC_5, CC_9, K4	CC_5, CC_9, K2b, KP	17a, 17b, D (new), C (new), B-a, A-a, K1a, N (piezo 3), KP, A-b, K2a, K2b	4	Monthly	Manual		Kenfig Corp	Dunes west of KP	CO, GR
K2a	Borehole	Kenfig	Sand and Gravel				n/a	K2b, KP, K1b, CC_5, CC_9, K4		17a, 17b, D (new), C (new), B-a, A-a, N (piezo 3), A-b	3	Monthly	Manual		Kenfig Corp	Pathway to Kenfig (S&G aquifer)	CO, GR

ID	Desc. (Name)	Locality	Monitored Aquifer / Water Body	Source[1]	Receptor[1]	Pathway[1]	Receptor Group	Pathway for receptors	Alt receptor sites	Alt pathway sites	Response Group[2]	Mon frequency	Mon Method	Critical[1,3]	Land controlled by	Comment	WMP[5]
K2b	Borehole	Kenfig	Dune Sand				Kenfig	KP, K1b, CC_5, CC_9, K4	CC_5, CC_9, K1b, KP	17a, 17b, D (new), C (new), B-a, A-a, N (piezo 3), A-b, K2a	4	Monthly	Manual		Kenfig Corp	Dunes south west of KP	CO, GR
KP[4]	Pond (Kenfig Pool)	Kenfig	Surface water (Dune Sand/S+G)				Kenfig	K1b, CC_5, CC_9, K4	CC_5, CC_9, K1b, K2b	K1a, N (piezo 3), A-b, K2a, K2b	3	Monthly	Manual		Kenfig Corp		CO, GR
N (piezo 3)	Borehole	Kenfig	Limestone				n/a	K2b, KP, K1b, CC_5, CC_9, K4		17a, 17b, D (new), C (new), B-a, A-a, A-b, K2a	3	Monthly	Manual		Private	Note – piezometers installed at 3 levels in this hole but all currently show almost exactly the same level	CO, GR
O	Borehole		Triassic				n/a				2	Monthly	Manual		TBC		GA
P	Borehole		Triassic				n/a				1	Daily	Auto		TBC		GA
PM	Sump	Pant Mawr	Surface water (Lst)				n/a	None (mitigation measures)		n/a	1	Daily	Auto		Tarmac		CO, GR
Q	Borehole		Limestone				n/a				2	Monthly	Manual		TBC		
R	Borehole		Triassic				n/a				2	Monthly	Manual		TBC		GA

See foot notes overleaf

1. Shaded = “yes”, unshaded = “no”
2. The Response Group reflects how rapidly the site responds to changes in level at the Quarry (1 is most rapid and 4 least rapid). The corresponding monitoring frequency is based on the rapidity of response so that responses can be seen in days for Group 1 whereas they may take months or years for Group 4.
3. Critical sites are defined in Section 1 and further discussion of site criticality is made in Section 4.1.1..
4. These sites are currently monitored by third parties. These are considered to be the most critical data sets collected by third parties and require a rapid response by the Quarry Operator should third party monitoring cease. Note that whilst Grove is currently operated by Tarmac, the monitoring is treated as third party as this could conceivably change in future.
5. Sites that are also included in the monitoring requirements of Grove and Cornelly WMPs are noted (GR - Grove, CO - Cornelly)

It is assumed that as part of the separate water management plans for Grove Quarry and Cornelly Quarry that there will be a requirement for water monitoring at sumps within respective operational quarry areas, and that the information arising from such monitoring will be disseminated between the Quarry companies as a continuation of the current joint approach to assessing the hydrogeological effects of both the individual and cumulative quarrying operations.

Monitoring of Receptors is subject to the agreement of the owners of the site and it is assumed that, as the monitoring is in their interest, this can be arranged by the Quarry Operator without any excessive penalties. Monitoring has only been proposed at those Receptors at which effects have been predicted from the proposed activities at the Quarry (SLR, 2014).

Monitoring at some of the Pathway sites is subject to ongoing agreements with the relevant landowners. These agreements cannot be guaranteed by the Quarry Operator in the long term. Procedures for dealing with a site that becomes unavailable for monitoring are given in Section 4.2.3.

The reference datum of each water level monitoring site will be re-surveyed at ten year intervals or at any point at which there is a step change in monitored water levels which might indicate that the datum has changed.

The depth of each borehole or dip well will be checked annually immediately prior to the issue of the Annual Report.

To ensure that the risk of lost data is minimised, there should always be two replacement loggers located at the Quarry site offices for use in the event of logger failure.

A.3 Surface Water Flows

The network of surface flow monitoring sites is shown on Figure A.1 and listed in Table A.3. All of these sites are defined as Receptor Monitoring Sites.

Table A.3 Stream Flow Monitoring

ID	Name	Type	Frequency
HL 6	Afon Fach	Stream	Monthly in summer
HL 11	Stormy Spring	Ephemeral Spring	Monthly in winter
HL9a	New Mill Farm springs	Stream	Monthly in summer
HL9b	New Mill Farm springs	Stream	Monthly in summer

Note: Summer in the context of this table includes the period April-September each year. Winter includes the period October to March.

A.4 Rainfall (Background)

The Quarry Operator will monitor rainfall in Cornelly Quarry by means of a tipping bucket rain gauge linked to a data logger to allow values to be measured at 15 minute intervals (unless this is being carried out by the Operator of Cornelly Quarry).

Rainfall is also monitored by Natural Resources Wales at Schwyll STW, Llety Brongu and Margam and by Bridgend County Borough Council at Kenfig (see more details of these sites in Appendix D). Until the Quarry Operator has collected sufficient data from the new rain gauge to allow a good correlation with data from these existing sites, for the purposes of understanding the relationship between current rainfall and historical rainfall, continuation of monitoring at these sites by third parties is essential to the operation of the WMP.

A.5 Groundwater Quality

Water samples will be collected as set out in Table A.4.

Table A.4 Water Quality Monitoring Sites

ID	Name	Type	Frequency	Sampling Method
GAS	Gaens Sump	Source	Monthly	Pumped/sump

Each sample will be analysed for the following parameters:

Field Parameters — Temp, EC, pH, Alkalinity

Laboratory Determinands — Major Ions (Ca, Mg, Na, K, Cl, HCO_3, SO_4, NO_3, NH_4, Sr)

A.6 Monitoring by Third Parties

Some hydrometric monitoring is carried out in the area by third parties as listed in Table A.5. The locations of the Critical sites are shown on Figure A.2.

The continuation of this monitoring is of benefit in providing additional information on the hydrogeological conditions in the area. Third party data that are considered to be Critical to the operation of the WMP are highlighted in **Bold** in Table A.5. These sites are duplicated in Sections A.2 to A.4 as appropriate.

Table A.5 Monitoring by Third Parties

ID	Name	Monitoring Activity	Frequency	Third Party
GRS	**Grove Quarry Sump**	**Pumping Rates**	**-**	**Quarry Operator[1]**
GRS	**Grove Quarry Sump**	**Water Level**	**-**	**Quarry Operator[1]**
CS	**Cornelly Quarry Sump**	**Pumping Rates**	**-**	**Quarry Operator**
CS	**Cornelly Quarry Sump**	**Water Level**	**-**	**Quarry Operator**
SC	South Cornelly	Water Levels	15 minutes	Natural Resources Wales
KP	**Kenfig Pool**	**Water Levels**	**15 minutes**	**Natural Resources Wales**
	Schwyll Spring rain gauge	**Rainfall**	**Daily**	**Natural Resources Wales**
	Llety Brongu rain gauge	**Rainfall**	**Daily**	**Natural Resources Wales**
	Margam rain gauge	**Rainfall**	**Daily**	**Natural Resources Wales**
CC_3,2	**Kenfig rain gauge**	**Rainfall**	**Weekly**	**Nature reserve staff**
I_BH18	Tythegston Landfill	Water Levels	Monthly	Landfill operator
I_COTTAGE	Tythegston Landfill	Water Levels	Monthly	Landfill operator
I_ROAD	Tythegston Landfill	Water Levels	Monthly	Landfill operator
I_TUSCA	Tythegston Landfill	Water Levels	Monthly	Landfill operator
I_WOODS	Tythegston Landfill	Water Levels	Monthly	Landfill operator
CC_1	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_2	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_24e	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_3	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_3,2	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC

ID	Name	Monitoring Activity	Frequency	Third Party
CC_3,2	Kenfig Dunes	Rain Gauge	Twice weekly	Bridgend CBC
CC_3,2a	Kenfig Dunes	Water Levels	Daily	Bridgend CBC
CC_34	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_4	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_5	**Kenfig Dunes**	**Water Levels**	**Monthly**	**Bridgend CBC**
CC_6	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_6,1	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_7	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_8	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_9	**Kenfig Dunes**	**Water Levels**	**Monthly**	**Bridgend CBC**
CC_10	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_11	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_117	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_12	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_139	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
CC_A0124	Kenfig Dunes	Water Levels	Monthly	Bridgend CBC
D1	Sewage treatment plant	Water Levels	Monthly	NRW
D2	Candleston Stream	Water Levels	Monthly	NRW
D3	Slack3	Water Levels	Monthly	NRW
D4	**Slack2**	**Water Levels**	**Monthly**	**NRW**
D5	Slack1 East	Water Levels	Monthly	NRW
D6	Slack1 mid	Water Levels	Monthly	NRW
D7	**Flood plain**	**Water Levels**	**Monthly**	**NRW**
D8	**Slack1 West**	**Water Levels**	**Monthly**	**NRW**
MM1	Merthyr Mawr lst	Water Levels	Monthly	NRW

1. At present Grove Quarry is not operational. The Quarry Operator is Tarmac Ltd. In future Grove Quarry will operate under its own WMP. The Monitoring requirements of that WMP have not been set yet.

Procedures for the situation where a third party ceases to monitor a site or does not make the information available or where the Quarry Operator considers that the QA procedures being applied do not conform to the requirements of Appendix B are set out in Section 4.2.4 of the WMP.

A.6 Additional Monitoring Under Different WMPs

Although not required under this WMP, some additional hydrometric monitoring will be carried out in the area under different WMPs (Grove and Cornelly Quarry WMPs) as listed in Table A.6. The locations of these sites are shown on Figure A.2.

Table A.6 Additional Monitoring by Under Different WMPs

ID	Name	Monitoring Activity	Frequency	WMP[1]
18b	Ty Talbot Farm	Borehole	Monthly	Gr
61	Tythegston	Borehole	Monthly	Co
CP	Cornelly	Settlement Pond	Daily	Co
D4	Merthyr Mawr Slack 2	Borehole	Monthly	Co
D7	Merthyr Mawr Flood plain	Borehole	Monthly	Co
D8	Merthyr Mawr Slack 1 West	Borehole	Monthly	Co
G	Tythegston	Borehole	Daily	Co
L	Merthyr Mawr	Borehole	Monthly	Co
RWC105		Borehole	Daily	Gr
RWC106		Borehole	Daily	Gr
S	Cornelly Quarry	Borehole	Monthly	Co
T	Newton Down	Borehole	Daily	Co
T_95/01	Airfield, Cornelly Quarry	Borehole	Daily	Co
U shallow	Merthyr Mawr	Borehole	Monthly	Co
U deep	Merthyr Mawr	Borehole	Monthly	Co

[1] Co-Cornelly, Gr-Grove

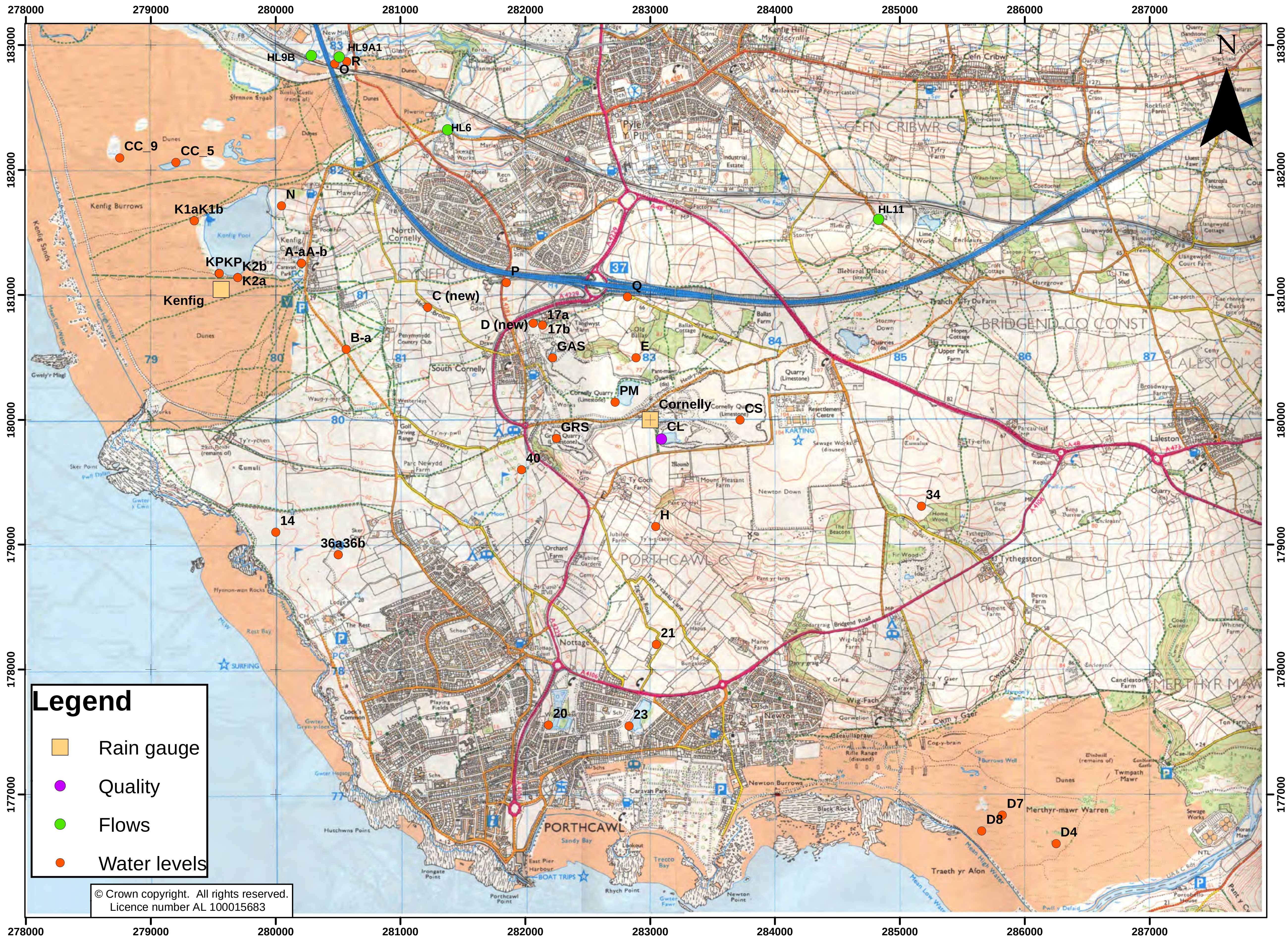

Figure A.1
Tarmac and critical 3rd party monitoring points for Gaens Quarry under this WMP

Date	Aug 2015	Drawn	KHB
Scale	1:30,000	Checked	MJS
Original	A3	Revision	6

File Reference
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Environment Specialists

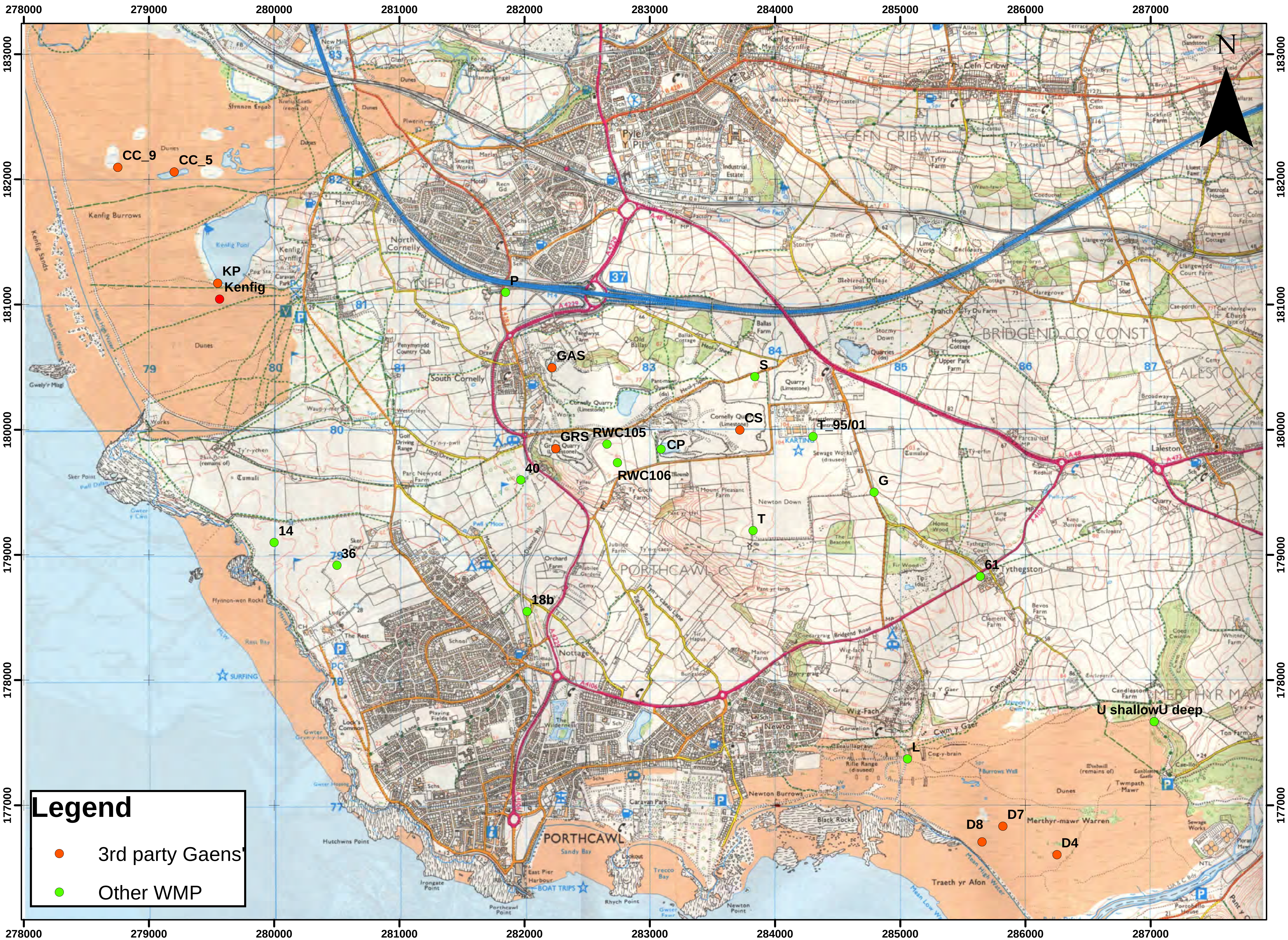

Figure A.2
3rd Party monitoring points for Gaens' Quarry WMP
and monitoring under Cornelly and Grove WMPs

Date	Aug 2015	Drawn	KHB
Scale	1:30,000	Checked	MJS
Original	A3	Revision	6

File Reference
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Environment Specialists

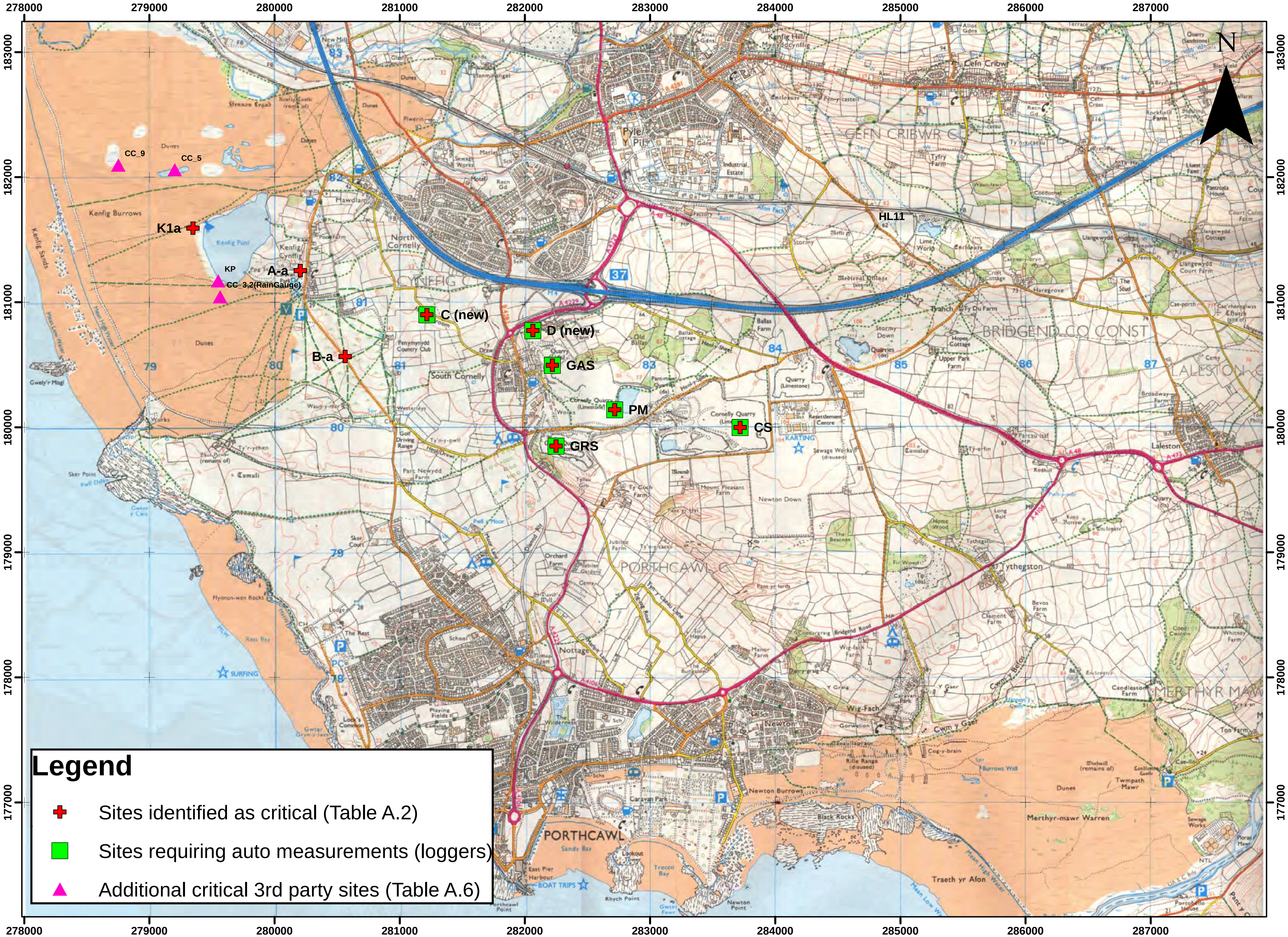


Figure A.3
Location of auto (Logger) and critical groundwater level sites for Gaens' Quarry under all WMPs

Date Aug 2015	Drawn KHB
Scale 1:30,000	Checked BCH
Original A3	Revision 6
File Reference O:\6227_Cornelly\reports\R17 EIA\Post submission WMP\Gaens\Figures\Superseeded\Figure A3_ gaens (Cornelly WMP 5.3).mxd	

Environment Specialists

Appendix B Quality Assurance (QA) Requirements

A rigorous approach will be adopted to ensuring the quality of all data collected during the monitoring period.

B.1 General Procedures

Quarry Abstractions: New meters have been fitted at the site and discussion with the manufacturers has indicated that the meters are within their calibration period. Meters will be re-calibrated as recommended by the manufacturers.

Water Levels: All monitoring datum points have been accurately surveyed in. All recent boreholes have been logged in detail (using geophysics in many cases) and constructed over selected intervals. A carefully designed field monitoring sheet is used for all field records (see example sheet). Water levels measured by data loggers are compared with manual readings on a monthly basis and any differences recorded and the loggers re-set. Water level measurements will comply with relevant sections of BS 6316: 1992.

A backup resource of two data loggers will be maintained to ensure continuity of monitoring.

Water Quality: All field measurements will be carried out to a standard specification using calibrated instruments. Laboratory analysis will be carried out by UKAS accredited laboratories.

Stream Flow Monitoring: The stream gauging exercise will be carried out as prescribed in BS 3680 Part 3Q: 1993.

An important part of QA for any monitoring network is regular review of the data (see Section 5).

B.1 Specific Monthly QA Checks

The Quarry Operator will apply a monthly QA check to the data collected. The details of these checks will be collated and presented in the Annual Report (Section 5.1). The monthly QA checks will include:

- An assessment of the completeness of the dataset. Where data are missing, recommendation consistent with the steps described in Section 4.2 will be taken.
- An assessment of any modifications to Planned Mitigation Measures that may be required.
- An assessment as to whether any of the information collected suggests that Contingency Measures are required (see Section 8 for a definition of what triggers Contingency Measures).

Cornelly Quarry water monitoring scheme; Record of monthly manual measurements						
Date:				**26th & 27th June '06**		
Weather at time of visit :				**26th - Light rain, 27th - Dry**		
Weather during previous '24hrs :				**25th - Dry with some rain overnight**		
Operative:				**J.Linton**		
Date	**Time**	**Reference**	**Location Description**	**Water Level (m below datum):**	**Additional Notes**	**Comments**
26/06/2006	11:30	**95/01**	Cornelly (Airfield)	38.29	Level reported by logger: 38.419	Logger downloaded: OK Battery: 99.05%
26/06/2006	11:25	**CR96/11**	Cornelly (Airfield)	63.38		
		95/04	Cornelly (Stormy)			Submerged
26/06/2006	09:15	**RWC100**	Grove	21.15	Level reported by logger: 21.123	Logger downloaded: OK Battery: 94.12%
26/06/2006	16:05	**A(1)**	50mm Blue Pipe	15.48		
		A(2)	20mm Black Pipe	14.11		
26/06/2006	16:10	**B(1)**	50mm Blue Pipe	23.1		
		B(2)	20mm Black Pipe	2.38		
26/06/2006	15:55	**C**		29.78		
26/06/2006	15:45	**D**		16.37		
26/06/2006	14:25	**G**		15.76	Note any ground water across field?	None
26/06/2006	14:05	**H**		33.78	Level reported by logger : 33.801	Logger downloaded: OK Battery: 65.58%
26/06/2006	14:55	**I**		Below	Blockage at 4.7m	
26/06/2006	14:50	**L**		1.45		
27/06/2006	12:10	**K1 50mm**		2.28		

		K1 25mm		0.57		
27/06/2006	11:45	**K2 50mm**		1.79		
		K2 25mm		1.65		
27/06/2006	11:45	**K3**		4.01		
27/06/2006	11:55	**N1 50mm**		4.01		
		N2 25mm		4.02		
		N3		3.99		
27/06/2006	14:00	**36(A)**	50mm Blue Pipe	16.13	Note Last Pumping Period	Last used 25/06/2006
		36(B)	20mm Black Pipe	Dry		
27/06/2006	10:05	**17**	Pond	0.1	Gauge Board	
27/06/2006	10:00	**17b**	Private Well	34.34		
26/06/2006	15:30	**20**	Pond	1.625		
26/06/2006	15:25	**23**	Pond	1.10		
26/06/2006	14:30	**34**	Pond	0	Gauge Board	
26/06/2006	14:35	**35**	Pond	Dry	Gauge Board	
26/06/2006	15:40	**40**	Well	17.77		Alternate borehole
26/06/2006	11:05	**Cornelly Pond**	Settlement Pond	4.28	Dipped from top of gauge board support	
26/06/2006	09:25	**Grove Sump**	Pond	0.48	Dipped from top of gauge board support	
		Pant Mawr	Pond	H&S Access Issues	Dipped from top of gauge board support	
		Stormy Down	Pond	H&S Access Issues		

Appendix C Assessment Criteria

C.1 Trigger Levels

Trigger Level Assessment Criteria have been defined for all for water level monitoring sites for which the development of Climate Based Assessment Criteria are not judged to be appropriate at present.

The Trigger Level Assessment Criteria set out in Table C.1 have been defined based on the minimum water level recorded at these sites in 2005 (a period of low groundwater level). Note that this excludes sites for which there was insufficient data in 2005 or for sites defined as Source monitoring points.

Table C.1 Trigger Levels Based on Summer 2005 Levels

ID	Trigger Level (mAOD)	Comment
17a	48.7	Pond
20	2.9	Pond
21	5.1	Tidal fluctuations.
23	3.7	Pond
34	65.2	Well dries up each year
61	-	No monitoring to date
A-b	-	Perched – dries up each summer
H	3.31	Tidal fluctuations.
T_95/04		Stormy Down sump – currently submerged and no recent data

C.2 Climate Based Assessment Criteria

The Climate Based Assessment Criteria for the remaining water level monitoring sites are illustrated in the following sheets and comments on the CBAC models are provided in Table C.2.

Table C.2 Climate Based Assessment Criteria

ID	Name/ Setting	Rainfall station	Description and recommendations	Overall quality of fit	WL trends observed	Cu-sum thresh old ranges	Std Dev error (of baseline data) (m)	Baseline data	Data excluded from baseline*
17b	Well	Margam	Abstraction well affected by periods of pumping; outlying low water level values are treated as suspect data. Under prediction of summer low levels in 2013 and of winter peak levels throughout.	Good	None	-10, 10	3.11	March 2002 – September 2014 (excluding pumping affected data)	17 measured points anticipated to be affected by pumping in the borehole.
40	Well	Margam	Abstraction well affected by periods of pumping; outlying low water level values are treated as suspect data. Model is over-predicting several large winter peaks. Good prediction of summer lows.	Very good	None	-10, 10	2.07	April 2002 – March 2013 (excluding pumping affected data)	03/02/2012 and 25/0202012 data does not reflect known winter high, possible abstraction.
A-a	Triassic	Margam	Data patchy from 2008 to 2013. Good prediction of summer lows.	Very good	None	-10, 10	0.88	September 2002 – March 2015 (not inclusive of excluded and suspect data)	All data pre-September 2002, poor fit to modelled data.19/05/2011 and 29/02/2012 suspect data.
B-a	Triassic	Margam	Under-prediction of peak values in recent years. Good prediction of summer lows.	Very good	None	-10, 10	0.90	September 2002 – March 2015 (not inclusive of excluded data)	All data pre-September 2002, poor fit to modelled data. 25/02/2012 suspect data.
Burrows Well (flow)	Limestone	Margam	Under prediction of winter 2008 high, over prediction of 2012 winter high. Review model calibration once further monitoring data is obtained.	Good	None	-20, 20	0.06 (m/s)	February 2008 – December 2010	January 2008 and all data post-2010, poor fit to modelled data.

ID	Name/ Setting	Rainfall station	Description and recommendations	Overall quality of fit	WL trends observed	Cu-sum thresh old ranges	Std Dev error (of baseline data) (m)	Baseline data	Data excluded from baseline*
C	Limestone	Margam	Large data gap followed by replacement of borehole. Model is calibrated to old borehole data, calibration to be reviewed following 3 years of new borehole data. Fit to new borehole data (since 2012) is good.	Very good	None	-10, 10	1.43	October 2001 – March 2008	All data from new borehole excluded
CC_5	Kenfig dunes	Kenfig	Under prediction of 2001/02 winter levels. Over prediction of summer 2011 levels. Measured groundwater levels are subject to long-term fluctuations resulting from inherent wet and dry periods.	Good	None	-10, 10	0.14	February 2007 – March 2015 (excluding poor fit data)	All data pre-2007 and March2011 – Oct 2012 data excluded. Higher frequency of monitoring in early data to 1990. Poor fit to modelled data.
CC_9	Kenfig dunes	Kenfig	Under prediction of elevated levels 2007 – 2011 and data over reporting period. Measured groundwater levels are subject to long-term fluctuations resulting from inherent wet and dry periods.	Good	None	-10, 10	0.18	February 2003 – March 2015 (excluding poor fit data)	All data pre-2003 and June 2011 – Dec 2012 data excluded. Higher frequency of monitoring in early data to 1990. Poor fit to modelled data.
D	Limestone	Margam	Large data gap followed by replacement of borehole. Model is calibrated to old borehole data, calibration to be reviewed following 3 years of new borehole data. Fit to new borehole data (since 2012) is good.	Good	None	-10, 10	2.11	January 2003 – April 2009	All data from new borehole excluded
D4	Merthyr Mawr Slack 2	Schwyll	Model is simultaneously under and over-predicting groundwater levels in the period 2007 – 2010.	Very good	None	-10, 10	0.11	January 2010 – March 2015	All data pre-2010, poor fit to modelled data.
E	Limestone	Margam	Location in close proximity to Cornelly and Gaens' quarries. Model fit to match early data - groundwater drawdown over data period (2004-2015).	Very good (baseline data only)	Drawdown of 6.8m over 11 year period	-10, 10	3.95	March 2002 – July 2004	All data post-July 2004 excluded due to declining groundwater trend.

ID	Name/ Setting	Rainfall station	Description and recommendations	Overall quality of fit	WL trends observed	Cu-sum thresh old ranges	Std Dev error (of baseline data) (m)	Baseline data	Data excluded from baseline*
G	Limestone	Margam	Poor fit to early data, not all summer lows well simulated.	Good	None	-10, 10	4.99	January 2003 – March 2015	All data pre-2003, poor fit to modelled data.
K1a	S&G aquifer	Kenfig	Simulation poor over review period, under-prediction of winter 2014/15 data. Affected by proximity to Kenfig Pool.	Very good	None	-10, 10	0.32	April 2003 – January 2015 (excluding suspect data)	February 2011 – August 2012, suspect data.
K1b	Dunes	Kenfig	Model over-predicting winter 2012/13 water levels and under-predicting 2014 levels. Affected by proximity to Kenfig Pool.	Very good	None	-10, 10	0.16	April 2003 – January 2015 (excluding suspect data)	June 2011 – December 2013, suspect data.
K2a	S&G aquifer	Kenfig	Good match to summer lows, some under prediction of high winter levels. Affected by proximity to Kenfig Pool.	Very good	None	-10, 10	0.43	March 2003 – March 2015 (excluding suspect data)	November 2011 – August 2012, suspect data.
K2b	S&G aquifer	Kenfig	Under prediction of 2014/15 winter water levels. Affected by proximity to Kenfig Pool.	Very good	None	-15, 15	0.42	August 2003 – March 2015 (excluding suspect data)	April 2012 – March 2013, suspect data.
KP	Pond	Kenfig	No change to calibration from previous years due to lack of data since 2010. Recalibrate model once further monitoring data is obtained.	-	-	-	-	-	-

ID	Name/ Setting	Rainfall station	Description and recommendations	Overall quality of fit	WL trends observed	Cu-sum thresh old ranges	Std Dev error (of baseline data) (m)	Baseline data	Data excluded from baseline*
L	Merthyr Mawr	Schwyll	Review model calibration once further monitoring data is obtained.	Very good	None	-10, 10	0.22	May 2001 – June 2013	None
N-a	Limestone	Margam	Model under-predicts highest peaks. Review model calibration once further summer monitoring data is obtained.	Very good	None	-10, 10	0.30	December 2002 – February 2015 (excluding suspect data)	30/05/2013, 26/06/2013 and 18/09/2013 suspect data.
O-a	Triassic	Margam	Model under predicts highest winter peaks, good match to summer lows.	Very good	None	-10, 10	0.21	October 2002 – March 2015 (excluding suspect data)	07/10/2010, 25/02/2012, 05/06/2013, and 07/05/2014 suspect data. June 2006 – February 2007 poor fit to modelled data.
P	Limestone	Margam	No new data since July 2013 – review model calibration once further monitoring data is obtained.	Very good	None	-10, 10	1.58	January 2004 – July 2013	All data pre-2004, poor fit to modelled data.
Q	Limestone	Margam	No new data since 2013 – review model calibration once further monitoring data is obtained.	Accept-able	None	-10, 10	6.10	October 2002 – May 2013	None
Quarry pumping (Cornelly)	Limestone	Margam	Preliminary CBAC to be finalised following sufficient data from an enhanced monitoring scheme for the quarry.	-	-	-	-	-	-
R-a	Triassic	Margam	Model poorly predicts winter peaks, good simulation to summer lows.	Very good	None	-10, 10	0.19	October 2002 – March 2015 (excluding suspect data)	05/06/2013, suspect data.

ID	Name/ Setting	Rainfall station	Description and recommendations	Overall quality of fit	WL trends observed	Cu-sum thresh old ranges	Std Dev error (of baseline data) (m)	Baseline data	Data excluded from baseline*
RWC105	Limestone	Margam	Location in close proximity to Cornelly and Grove quarries, early data (1998-2003) affected by pumping. Groundwater levels appear stable from 2004 onwards.	Good	Drawdown of 10 m over 7 years. Levels now stable.	-10, 10	2.63	January 2003 – March 2015	All data pre-2003, data influenced by pumping.
RWC106	Limestone	Margam	Same comments apply as for RWC105.	Good	Drawdown of 6 m over 7 years. Levels now stable.	-10, 10	3.25	January 2003 – March 2015	All data pre-2003, data influenced by pumping. 01/06/2006 and 29/06/2012, suspect data.
South Cornelly	Limestone	Margam	Simulation poor prior to 2003. Large Cu-sum axis due to higher frequency of monitoring. Cu-sum suggests increase in water levels since late 2013.	Good	Increase since late 2013	-300, 300	1.24	Sept 2002 – January 2013	Apr 1995 – March 2002 poor fit to modelled data. March 2002 – Sept 2002 suspect data.
T_95/01	Airfield	Margam	Location in close proximity to Cornelly quarry, early data (1995 – 2003) affected by pumping. Model under predicts winter peaks, summer lows are better simulated. Large Cu-sum axis due to higher frequency of monitoring.	Accept-able	Levels fluctuating pre-2003. Levels now stable.	-300, 300	6.93	January 2003 – March 2015	All data pre-2003, data influenced by pumping.

~A downward value trend (shown as an upward line on the graph) in Cu-sum (Si) statistics indicates that groundwater levels are under-simulated by the model and vice versa.
*Where a poor data fit is present, error statistics are enlarged reducing their sensitivity to groundwater level trends. Such data has been removed where indicated.

Sites for which there are currently insufficient data to define either a Trigger Level or a CBAC are listed in Table C.3 with the sites that are considered to represent conditions at that site.

Table C.3 Sites with Insufficient Data and Alternative Sites

ID	Name/Setting	Nearest representative CBACs/Trigger level	Distance to nearest CBACs/Trigger level location (m)
A-b	Sand and gravel	K2a	520
D7	Dune sand	D4	610
D8	Dune sand	D4	490
S	Limestone	T/95_01	670
T	Limestone	G	1010
U (shallow)	Dune sand	D4	1310
U (deep)	Limestone	L	1990
14	Well	40	2030
65	Well	B-a	1540
18b	Well	40	1050
36	Well	40	1610

C.3 Assessment Criteria for Flow Sites

There is currently insufficient data available from the stream flow monitoring sites (HL6, HL9, Hl11, HL13, HL14, HL15) to allow reasonable Trigger Level or Climate Based Assessment Criteria to be developed. For these sites, Deviations will in the short term be assessed by reference to the Assessment Criteria of nearby water level monitoring sites as set out in Section 6.7.3.

C.4 Assessment Criteria for Quarry Dewatering

As discussed in Section 6.4.3, there is only intermittent dewatering occurring at the the Quarry and therefore there is insufficient data to allow a reasonable Trigger Level or Climate Based Assessment Criteria to be developed. In the short term, Deviation at this site will be assessed by means of the CBACs for water levels in the nearby boreholes.

Runoff Calculation Parameters (Location 17b)

N.B. This is an abstraction well so is affected by pumping

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0.01	0.035	0.275
20	0	0.01	0.025

Rainfall station: Margam

GW Abstractions (Ml/d)

0	
Slow flow split	
1	SW discharge
0	GW discharge

Number of days 10682

General parameters

Head Change Calculation

Rainfall Multiplier	1	
PE Multiplier	1	

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1420082	0.01	14
GW	1420082	0.01 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	80	days
T Fast	80	days
Slow store max	100	mm

Stats

Baseline dataset for calculation of error statistics:
March 2002 - September 2014 (excluding pumping affected data)

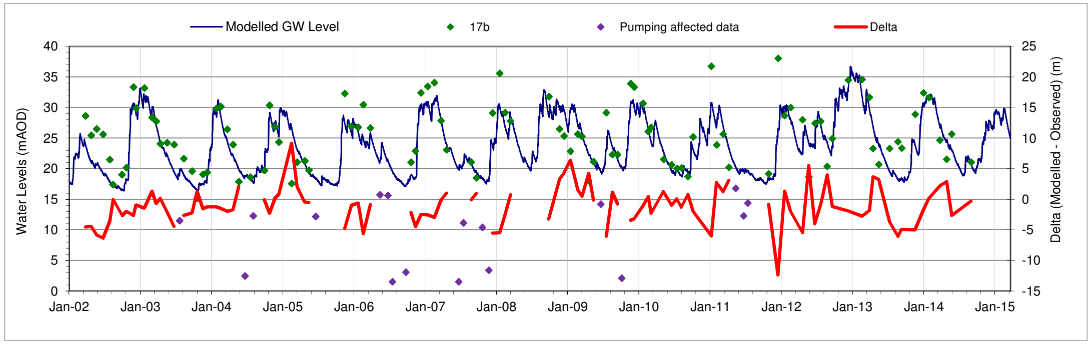
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-1.08	m
ST Dev Error	3.11	m
Dummy value for Z_i	0	

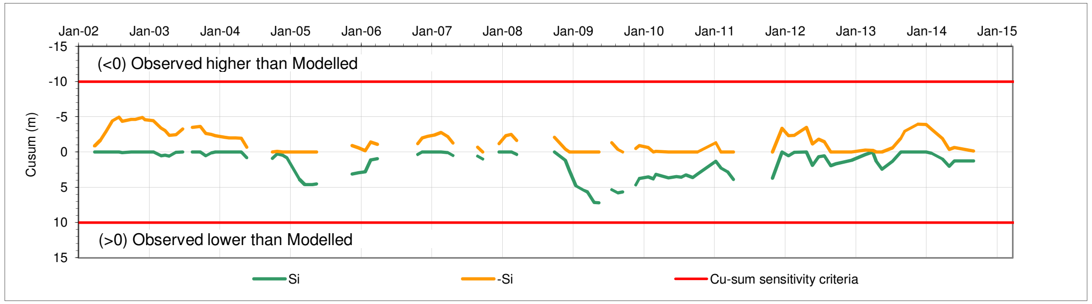
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**5570**

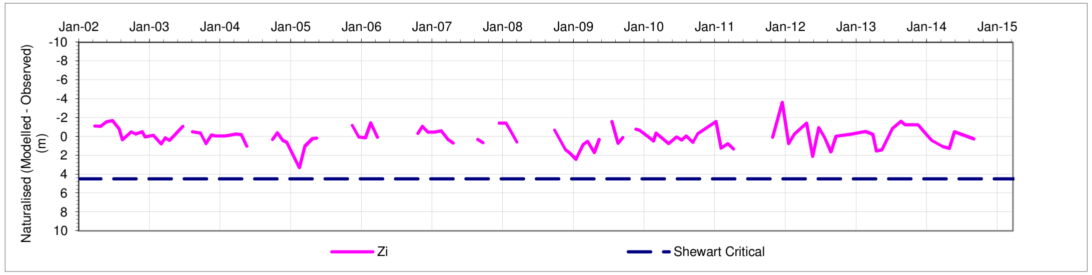
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location 40)

N.B. This is an abstraction well so is affected by pumping

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	5	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,400,082	0.015	2
GW	1,400,082	0.015 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	1	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	95	days
T Fast	95	days
Slow store max	150	mm

Stats

Baseline dataset for calculation of error statistics:
April 2002 - March 2013 (excluding suspect data)

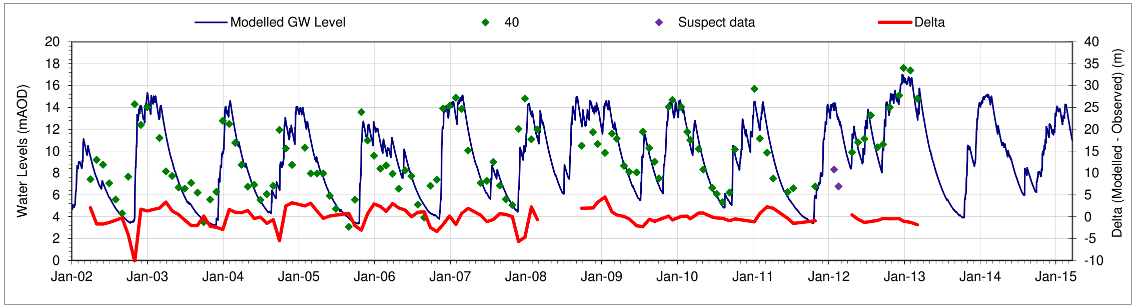
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.16	m
ST Dev Error	2.07	m
Dummy value for Z_i	0	

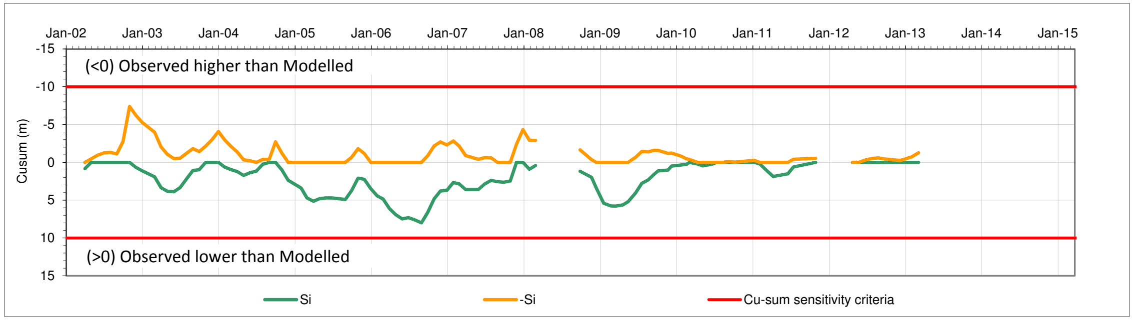
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**1953**

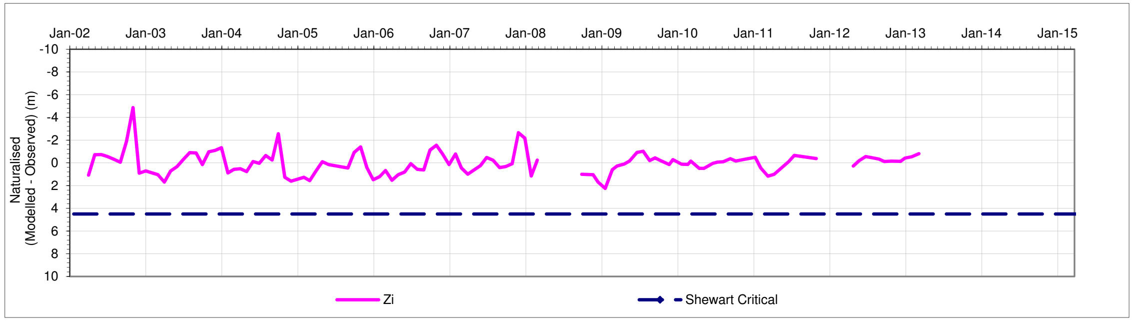
* If PEST is used - PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location A-a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.30
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0.00	0.00	0.00
20	0.00	0.00	0.00

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682.00

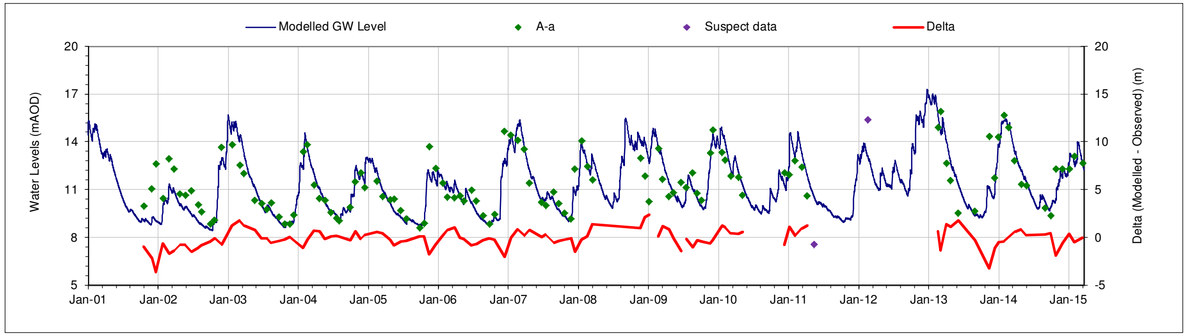
General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.033	7.500
GW	1,756,799	0.033	fracture

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	93	days
T Fast	93	days
Slow store max	150	mm



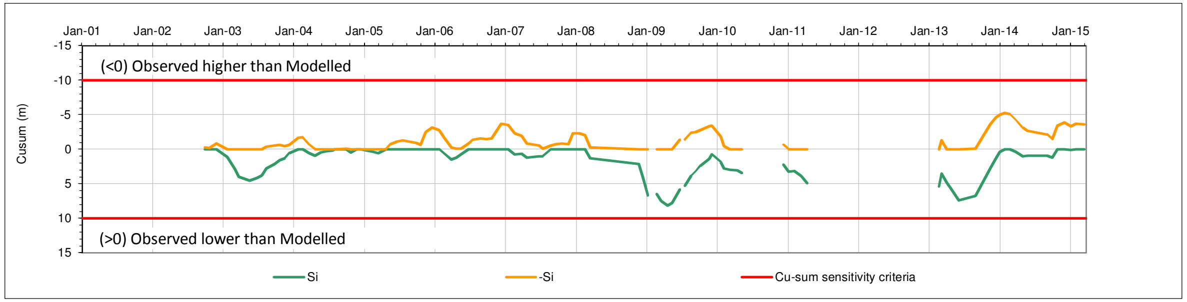
Stats

Baseline dataset for calculation of error statistics:
September 2002 - March 2015 (excluding pumping affected data)

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	0.08	m
ST Dev Error	0.88	m
Dummy value for Z_i	0	

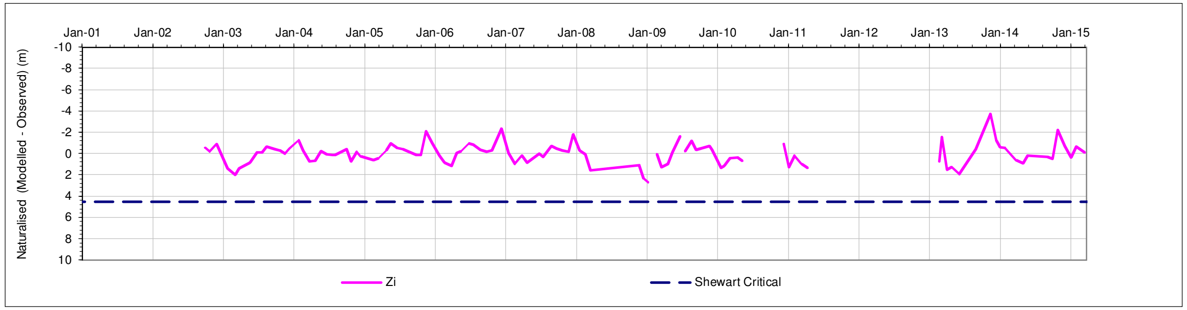
Phi_calibration - last loaded PEST run	n/a
Phi_calibration - spreadsheet calcs	668

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations



PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	



Runoff Calculation Parameters (Location B-a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.04	5.7
GW	1,756,799	0.04 fracture	

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	90	days
T Fast	90	days
Slow store max	150	mm

Stats

Baseline dataset for calculation of error statistics:
September 2002 - March 2015 (excluding suspect data)

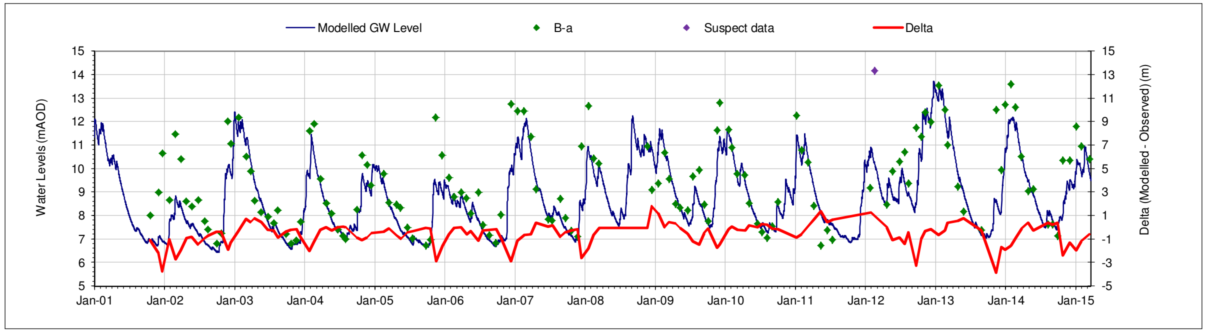
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.46	m
ST Dev Error	0.90	m
Dummy value for Z_i	0	

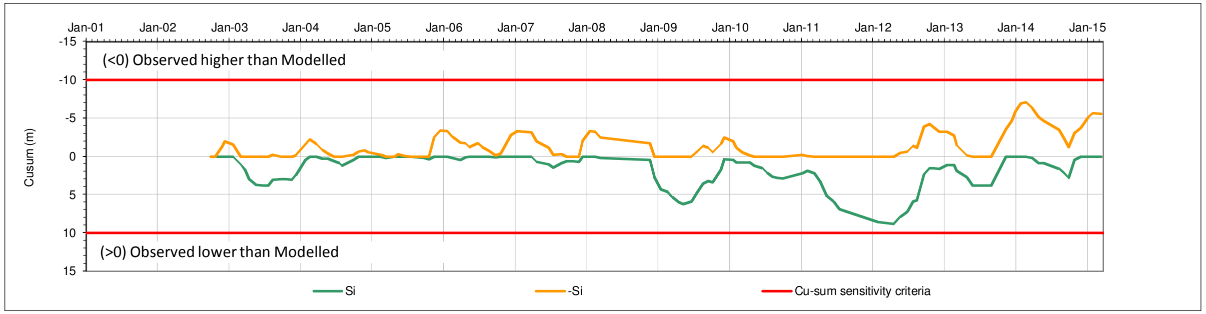
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**762**

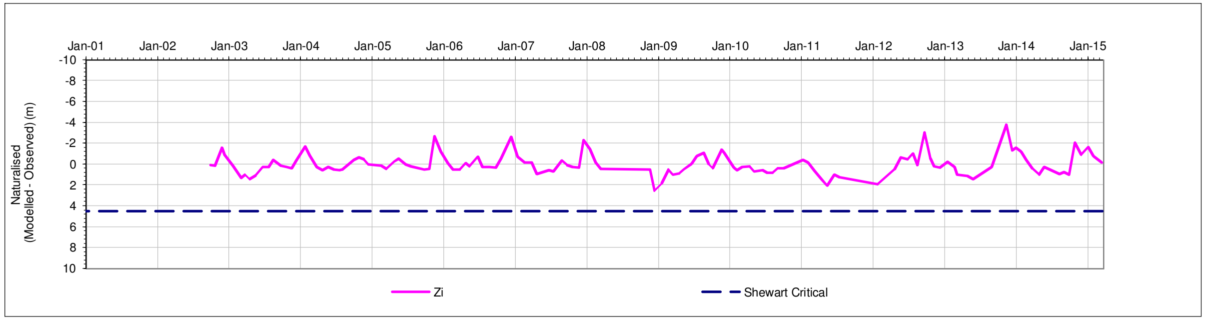
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Burrows Well)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	10	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Schwyll

Rainfall Multiplier	1
PE Multiplier	1
Runoff multiplier	1

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	2,500,000	0.002	45
GW	2,500,000	0.002	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

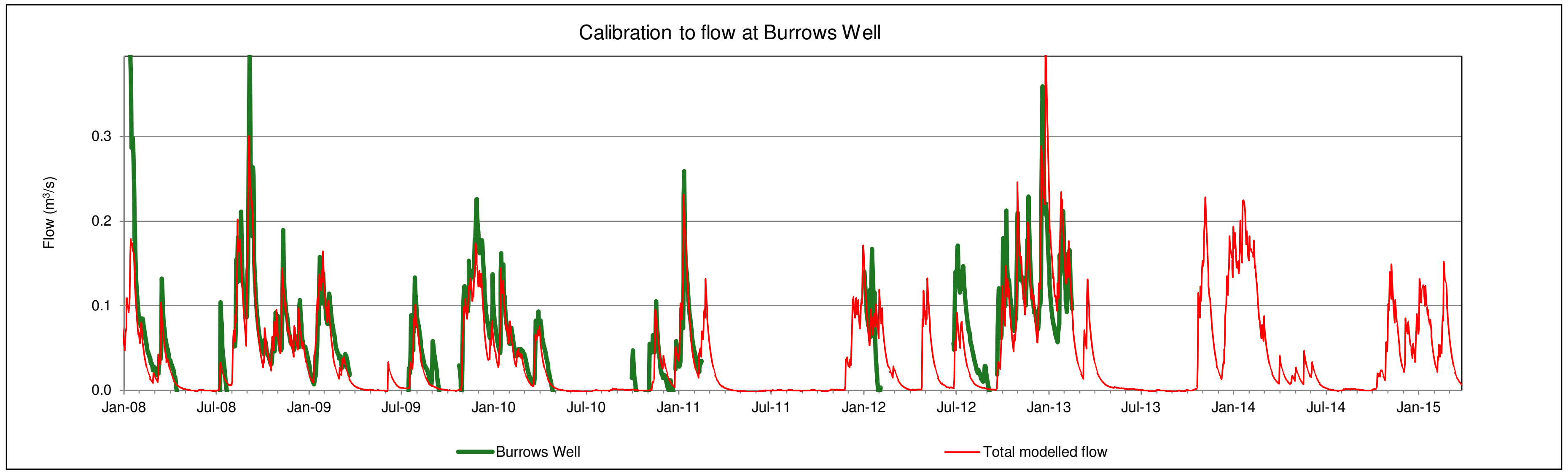
Stores Parameters

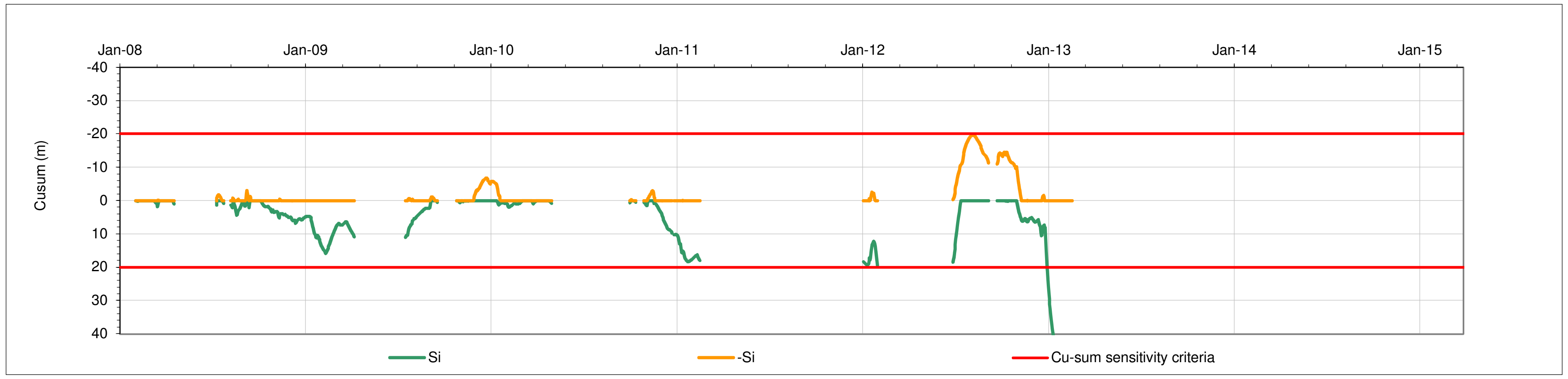
% Slow	100	%
Fast_store_Starting_Volume	0	mm
Slow_store_Starting_Volume	0	mm
GW_Abstractions__Ml_d	0	Ml/d
Slow_flow_split	1	-
Slow_store_max	200	mm
TFast	70	days
TSlow	10	days

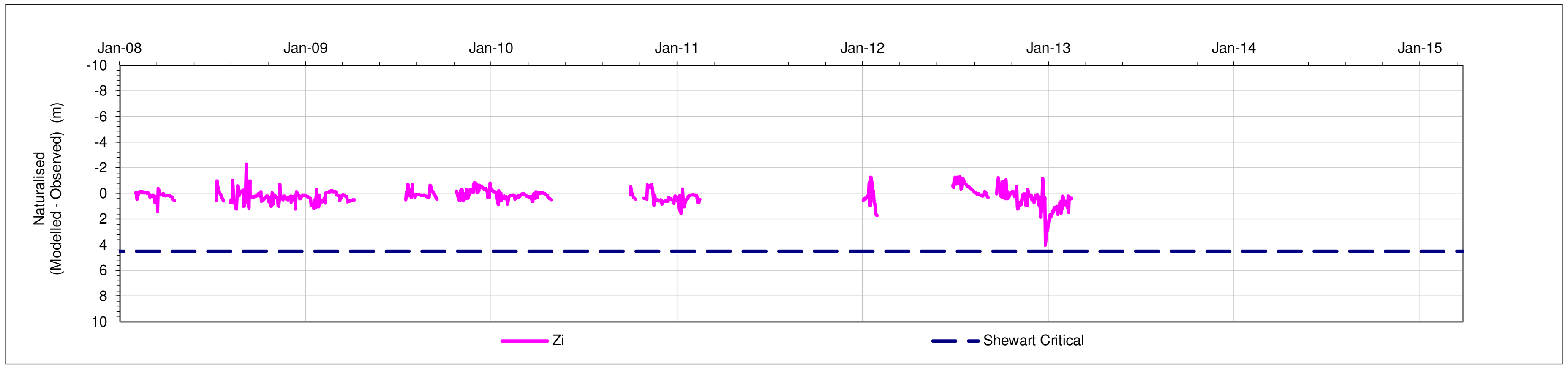
Baseline dataset for calculation of error statistics:
February 2008 - December 2010

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.02	m3/s
ST Dev Error	0.05	m3/s
Dummy value for Z_i	0	

LTA Burrows Well flow rate *January 1986 - April 2015*	0.04	m3/s
Actual average Burrows Well flow rate *January 2008 - February 2013*	0.09	m3/s







Runoff Calculation Parameters (Location C)

N.B. Model is calibrated to Old borehole C only

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d) 0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.013	8.8
GW	1,756,799	0.013 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	100	days
T Fast	100	days
Slow store max	60	mm

Stats

Baseline dataset for calculation of error statistics:
October 2001 - March 2008

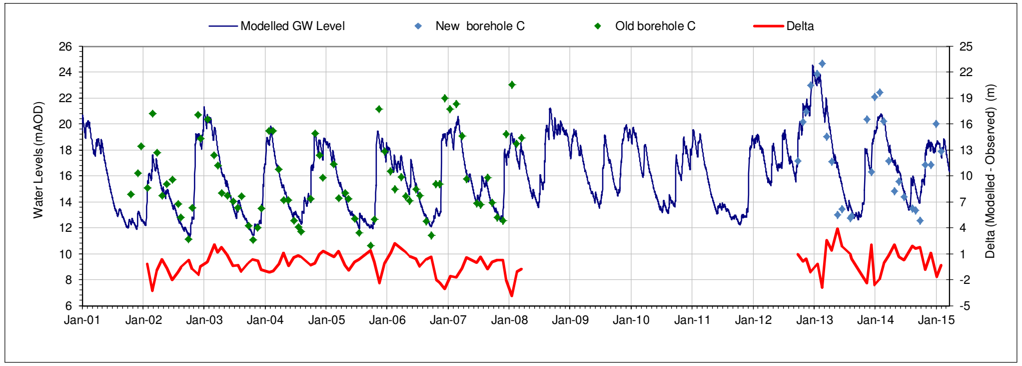
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.33	m
ST Dev Error	1.43	m
Dummy value for Z_i	0	

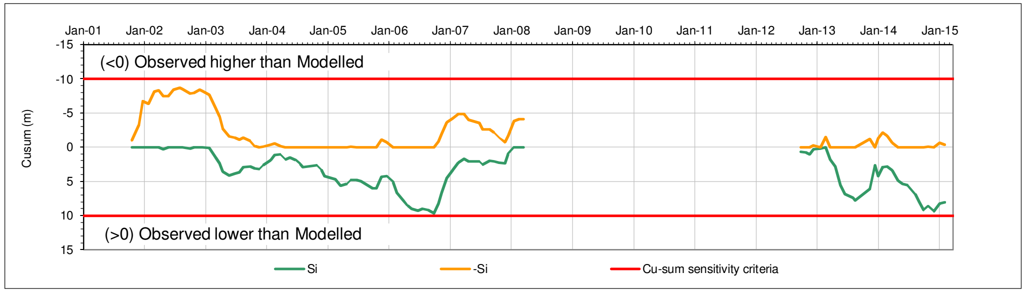
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**581**

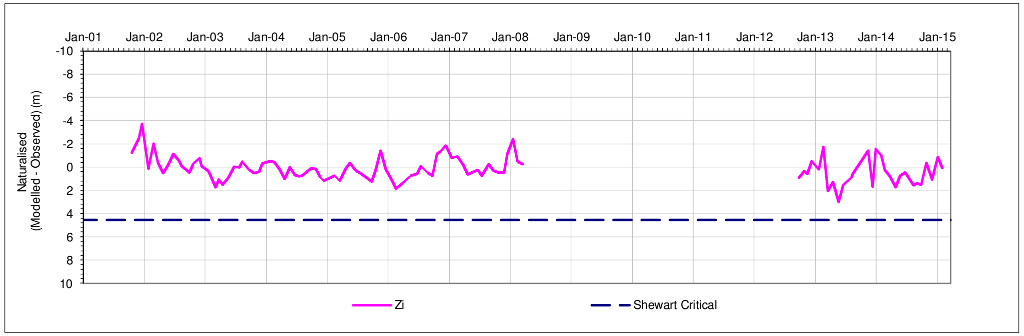
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (CC_5)

N.B. K value for dune sand CBACs is lower than the standard (0.25 m)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier	1
PE Multiplier	1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	3,560,000	0.2	9.5
GW	3,560,000	0.2 fracture	

User-defined time series

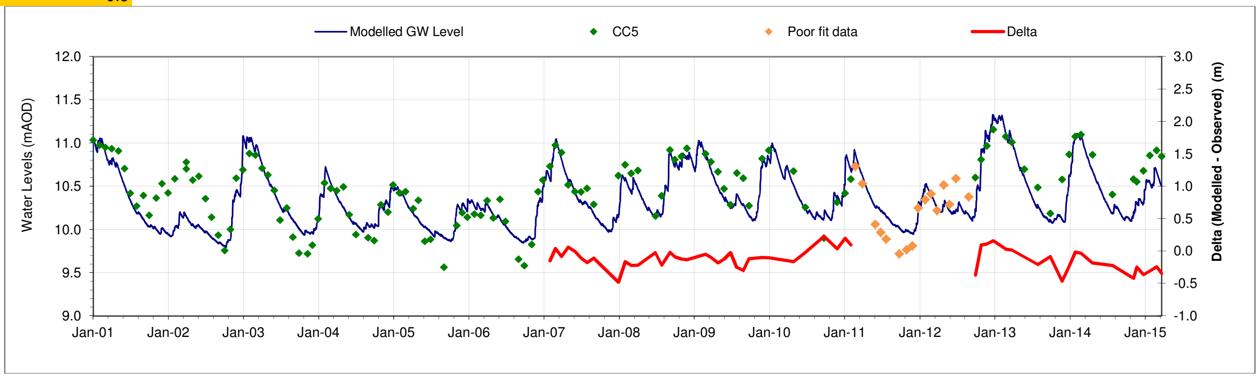
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

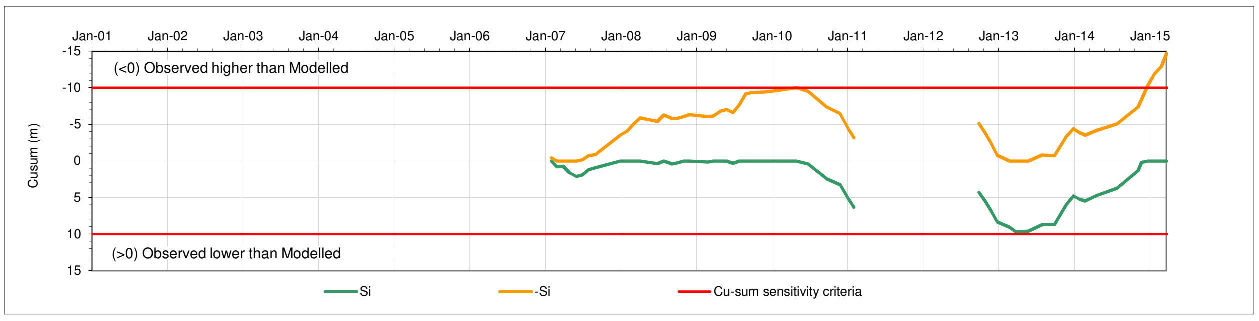
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	150	days
T Fast	150	days
Slow store max	200	mm

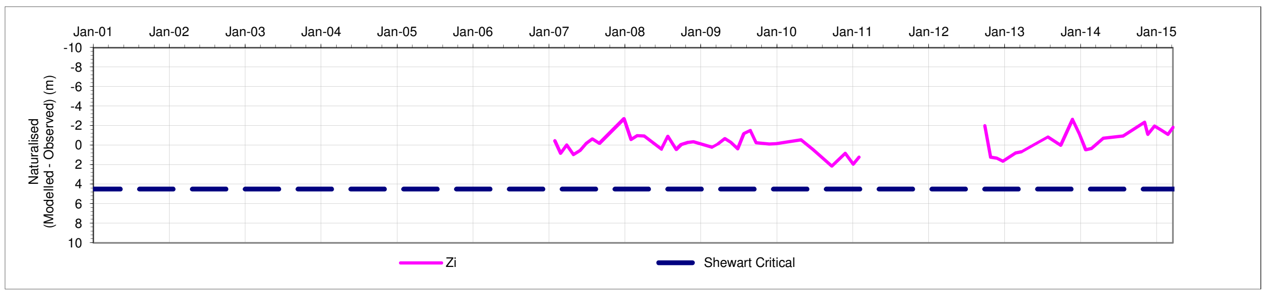
Stats

Baseline dataset for calculation of error statistics:
February 2007 - March 2015 (excluding poor fit data)

K (not permeability!!)	0.05	m
Mean Error (Modelled - Observed	-0.08	m
ST Dev Error	0.14	m
Dummy value for Z_i	0	

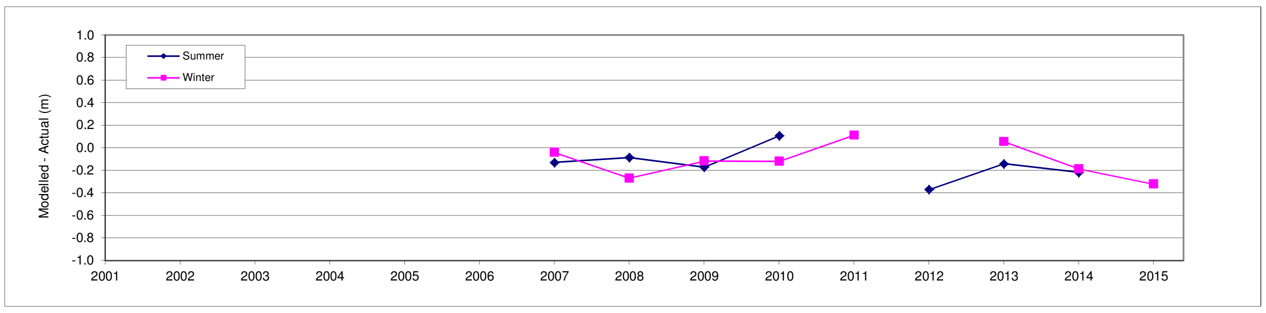


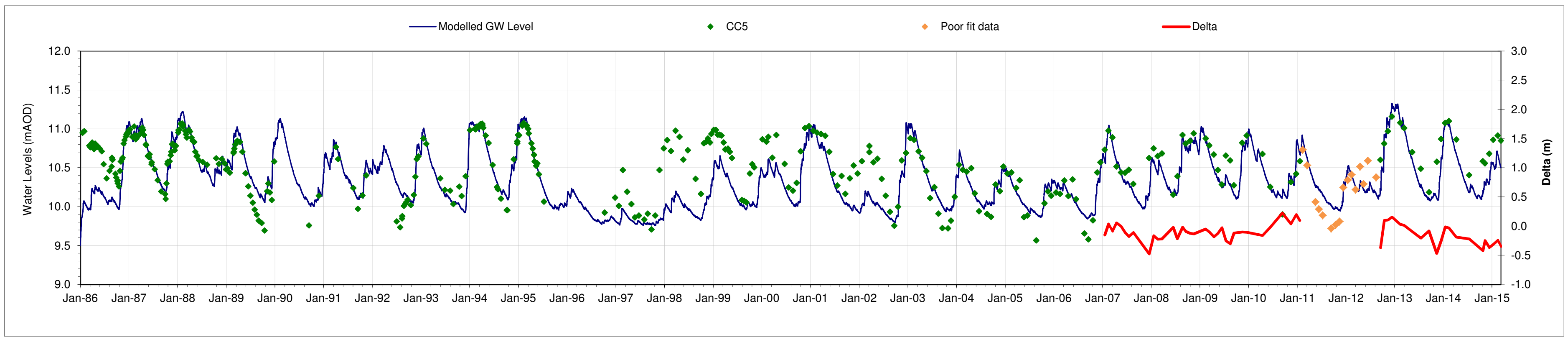




NOTE: Summer goes from July to October Included;
Winter goes from November to June the following year.

Mean summer error	-0.15	m
Max Summer error	0.11	m
Min Summer error	-0.37	m





Runoff Calculation Parameters (Location CC_9)

N.B. K value for dune sand CBACs is lower than the standard (0.25 m)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	3,560,000	0.18	8.1
GW	3,560,000	0.18 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	150	days
T Fast	150	days
Slow store max	120	mm

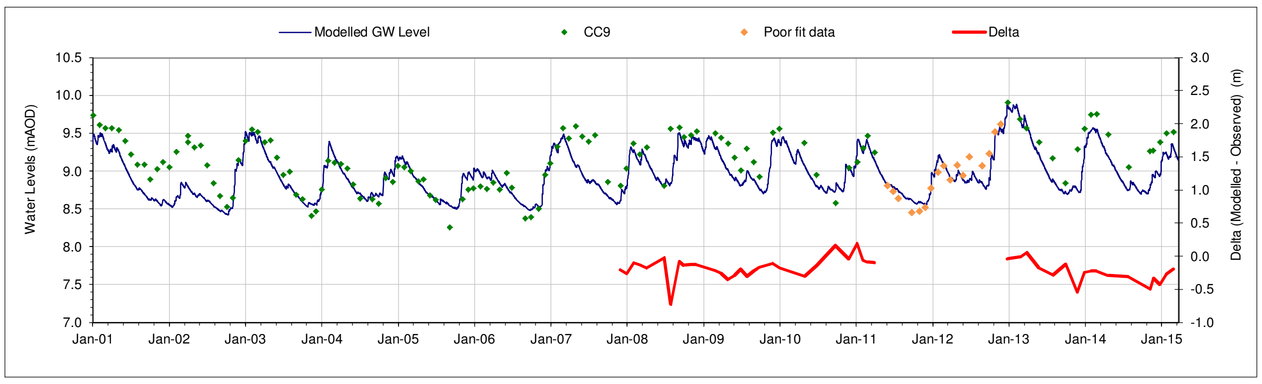
Stats

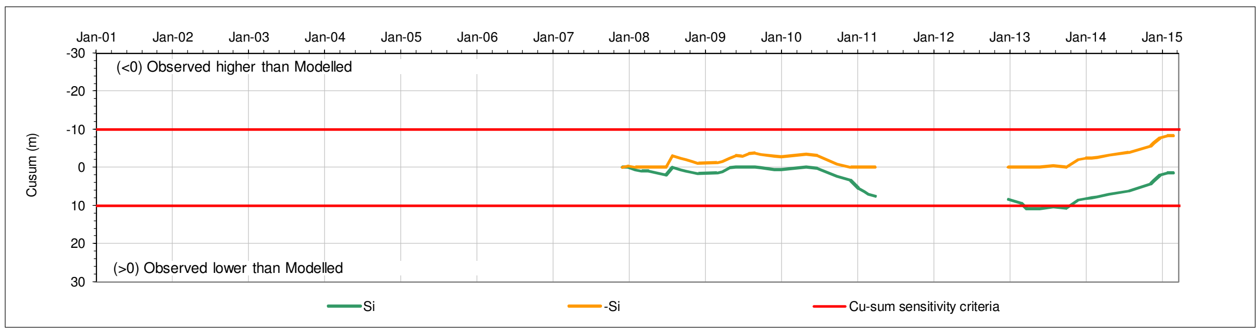
Baseline dataset for calculation of error statistics:
February 2003 - March 2015 (excluding poor fit data)

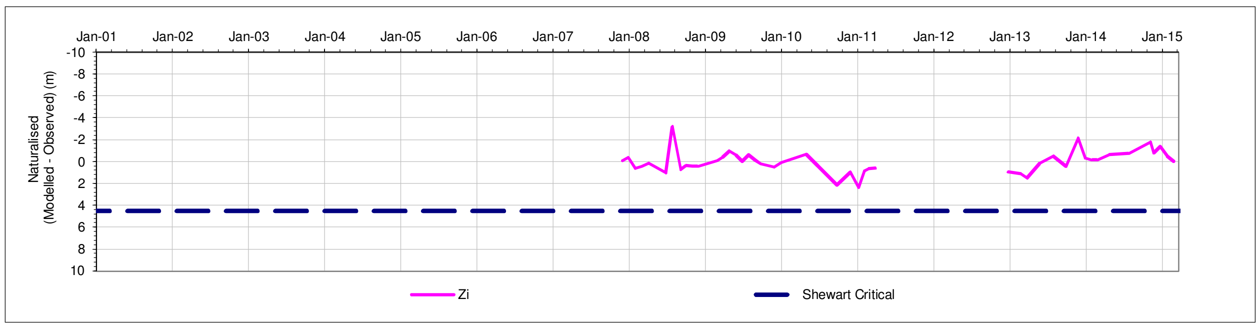
K (not permeability!!) 0.05 m

Mean Error (Modelled - Observedl) -0.19 m
ST Dev Error 0.16 m

Dummy value for Z_i 0

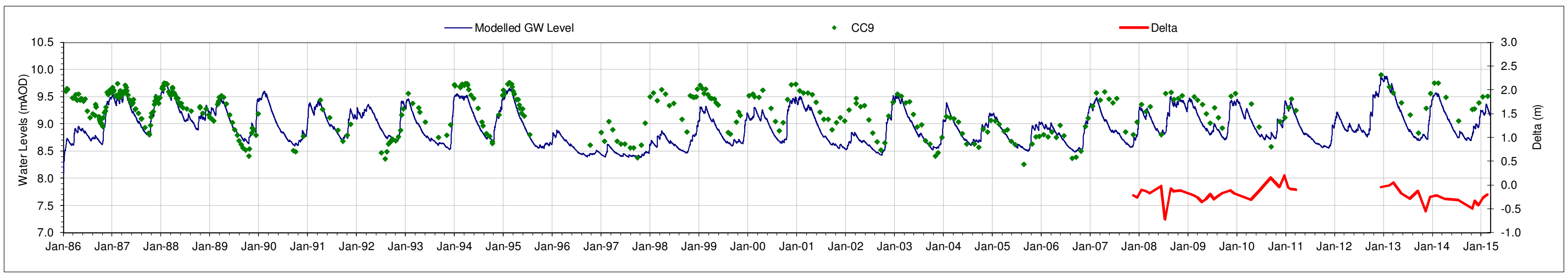






NOTE: Summer goes from July to October Included;
Winter goes from November to June the following year.

Mean summer error -0.15 m
Max Summer error 0.17 m
Min Summer error -0.37 m



Runoff Calculation Parameters (Location D)

N.B. Model is calibrated to old borehole D only

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.016	17
GW	1,420,082	0.016 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

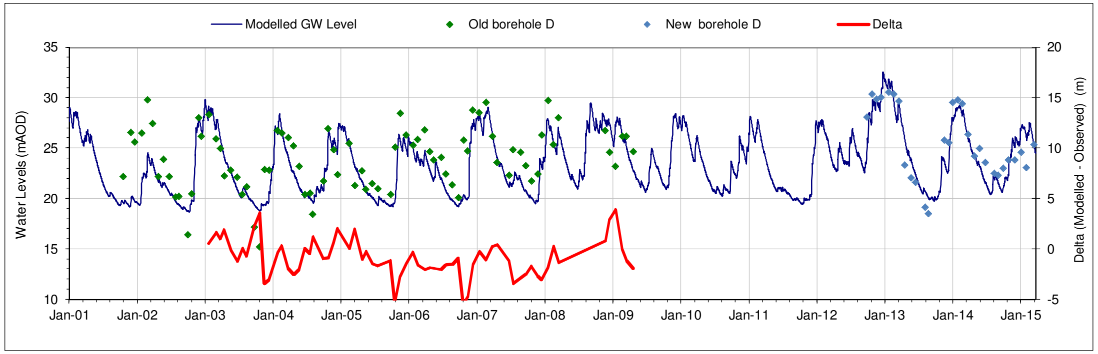
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

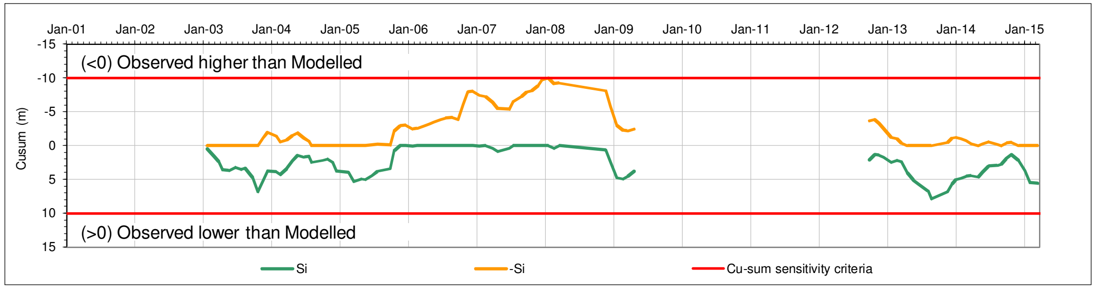
Runoff multiplier	1	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	95	%
T Slow	85	days
T Fast	85	days
Slow store max	100	mm

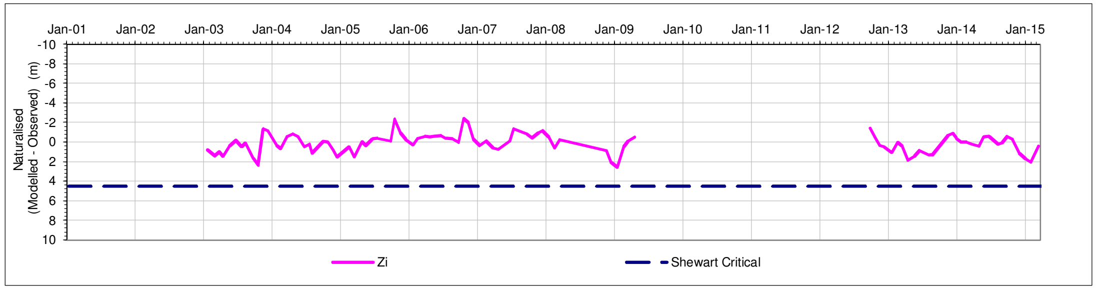
Stats

Baseline dataset for calculation of error statistics:
January 2003 - April 2009

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed	-0.86	m
ST Dev Error	1.89	m
Dummy value for Z_i	0	







Runoff Calculation Parameters (Location D4) **N.B. K value for dune sand CBACs is lower than the standard (0.25 m)**

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Schwyll

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1756599	0.24	7.5
GW	1756599	0.24	fracture

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

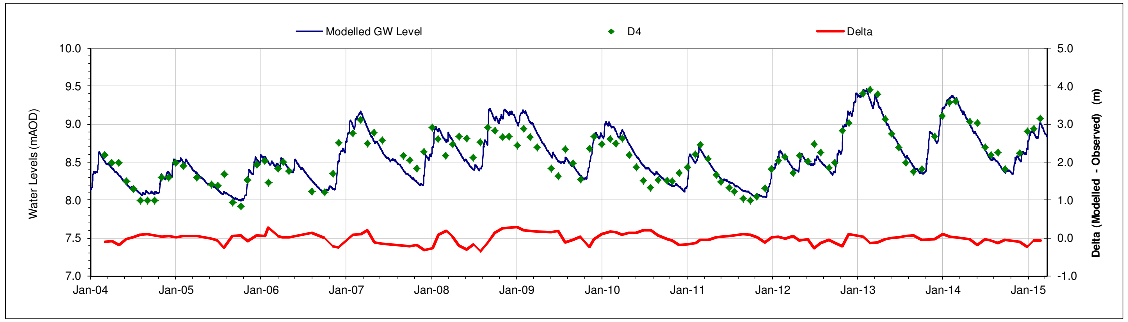
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

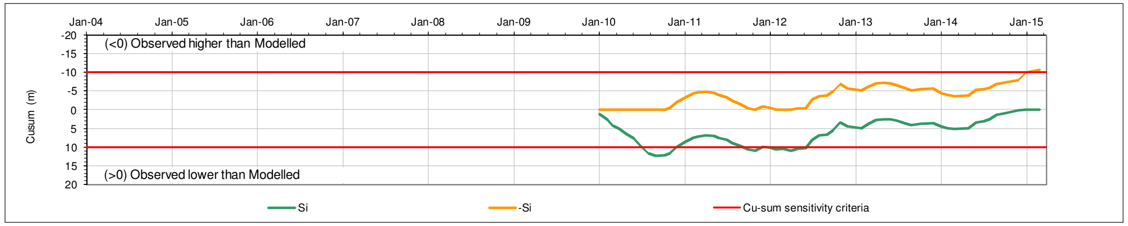
Runoff multiplier	1	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	200	days
T Fast	200	days
Slow store max	220	mm

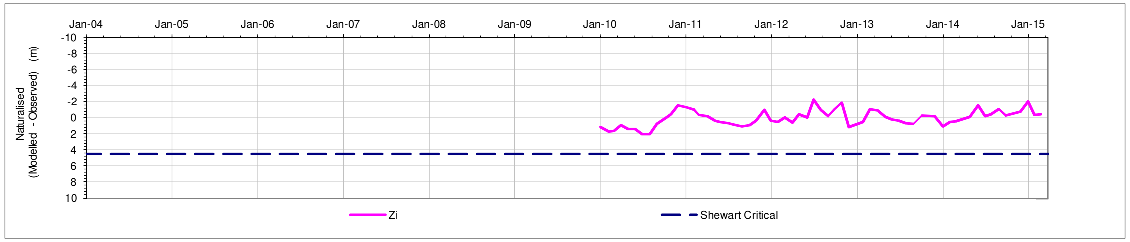
Stats

Baseline dataset for calculation of error statistics:
January 2010 - March 2015

K (not permeability!!)	0.05	m
Mean Error (Modelled - Observed)	-0.01	m
ST Dev Error	0.11	m
Dummy value for Z_i	0	

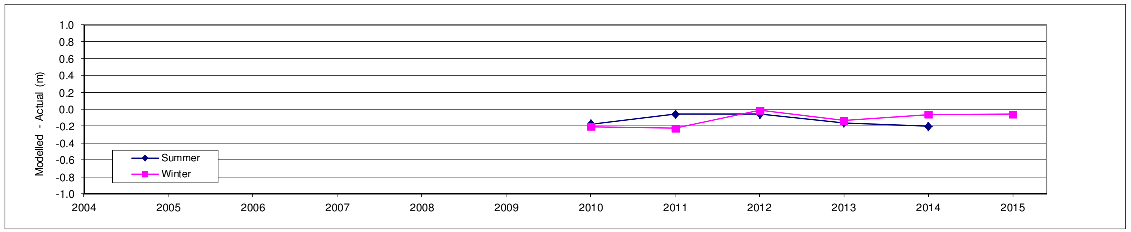






NOTE: Summer goes from July to October Included;
Winter goes from November to June the following year.

Mean summer error	-0.13	m
Max Summer error	-0.01	m
Min Summer error	-0.22	m



Runoff Calculation Parameters (Location E)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	5	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Rainfall station: Margam

Number of days 10682

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.007	18.5
GW	1,420,082	0.007 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	70	%
T Slow	50	days
T Fast	50	days
Slow store max	100	mm

Stats

Baseline dataset for calculation of statistics:
March 2002 - July 2004

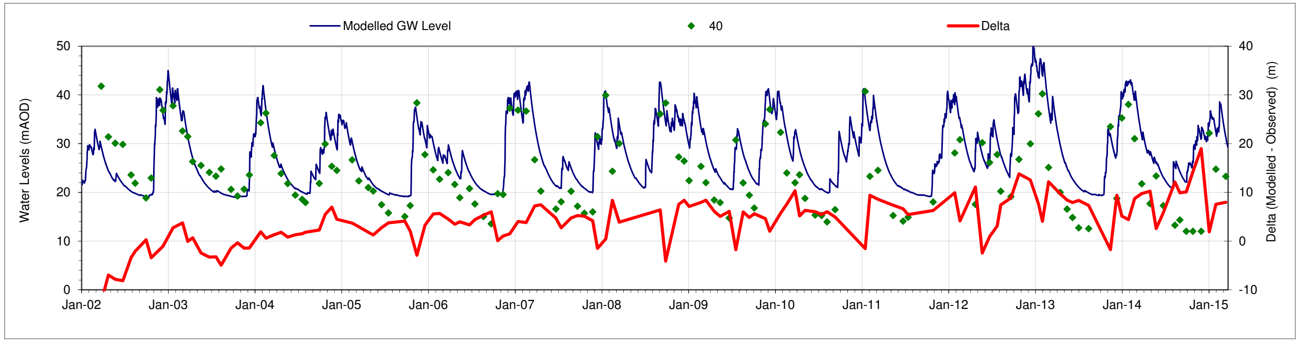
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	0.51	m
ST Dev Error	3.95	m
Dummy value for Z_i	0	

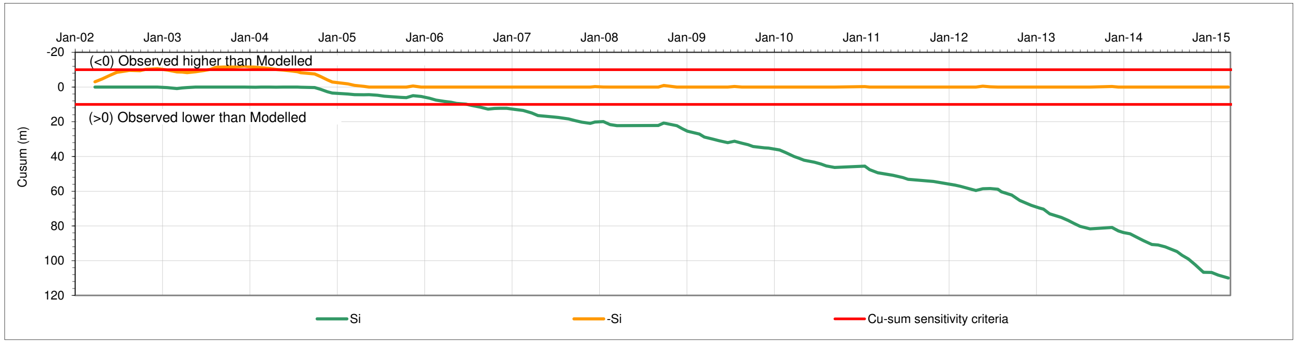
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**18416**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

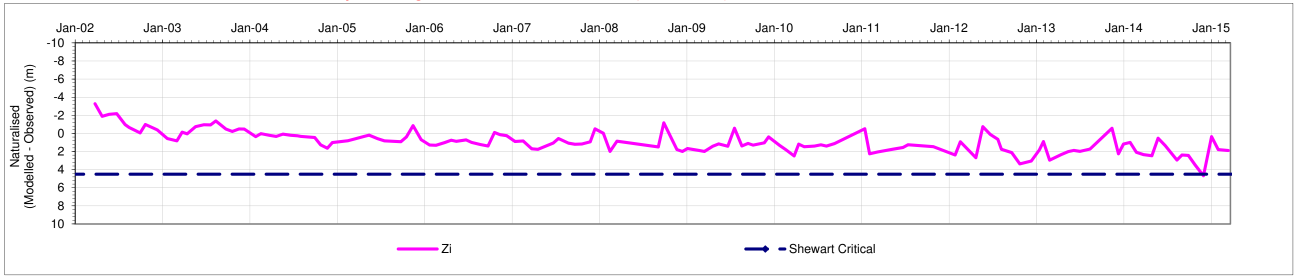
PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	





N.B. The scale on the cusum plot is larger than the CBACs standard (10 m, -10 m)



Runoff Calculation Parameters (Location G)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.004	30.00
GW	1,420,082	0.004 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	95	%
T Slow	120	days
T Fast	120	days
Slow store max	90	mm

Stats

Baseline dataset for calculation of error statistics:
January 2003 - March 2015

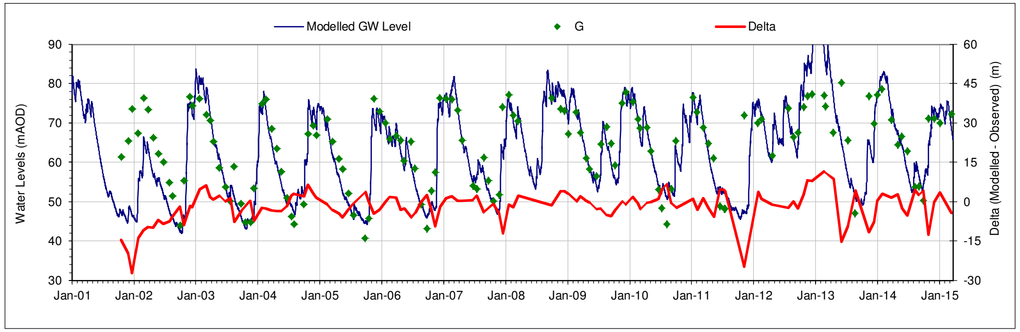
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.54	m
ST Dev Error	4.99	m
Dummy value for Z_i	0	

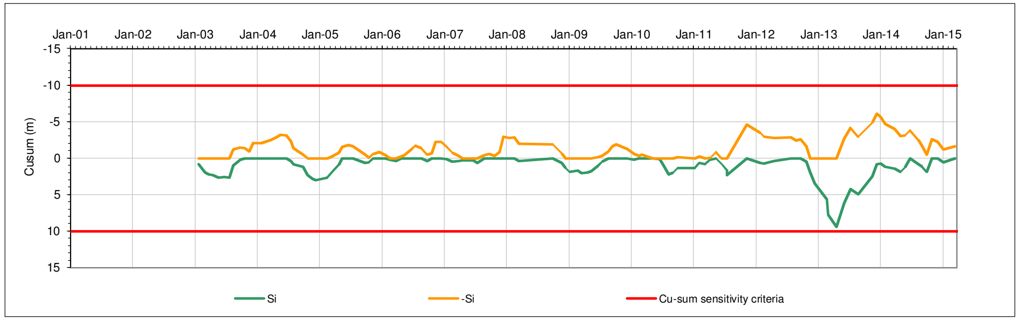
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**5362**

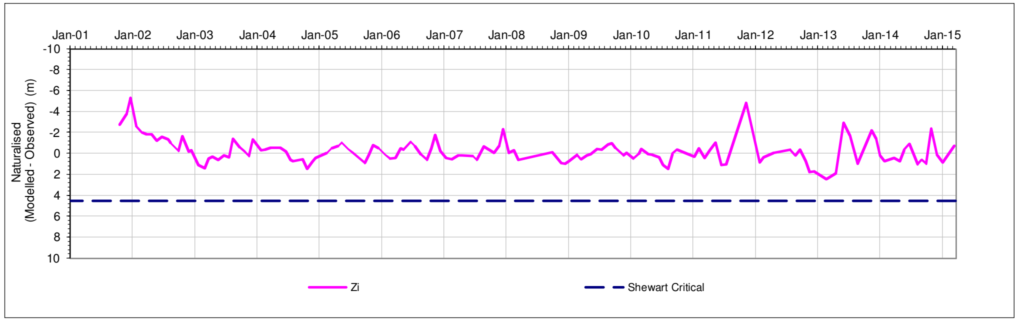
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location K1a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	10	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.11	7.5
GW	1,756,799	0.11 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	95	%
T Slow	110	days
T Fast	110	days
Slow store max	250	mm

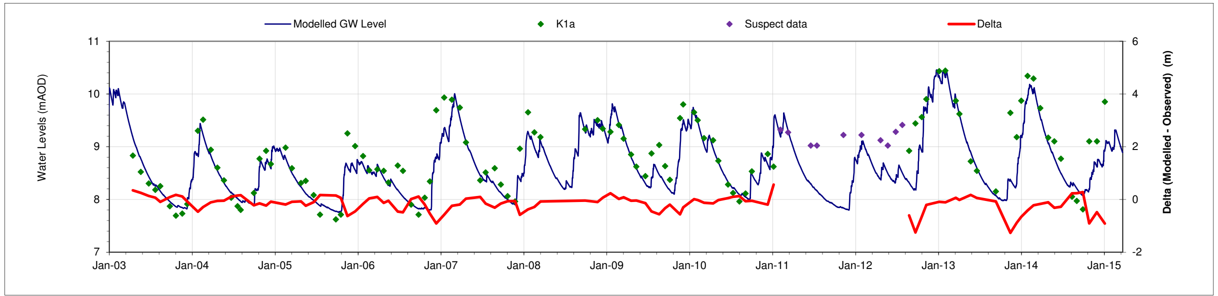
Stats

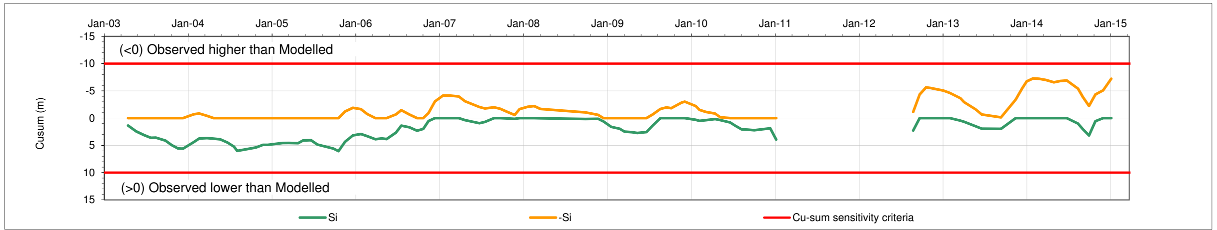
Baseline dataset for calculation of error statistics:
April 2003 - January 2015 (excluding suspect data)

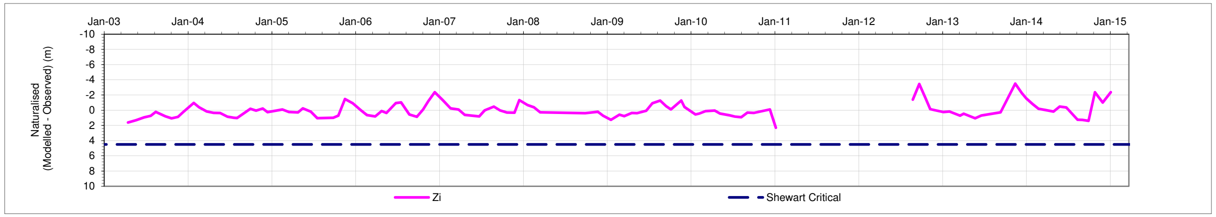
K (not permeability!!) 0.25 m

Mean Error (Modelled - Observed) -0.16 m
ST Dev Error 0.32 m

Dummy value for Z_i 0

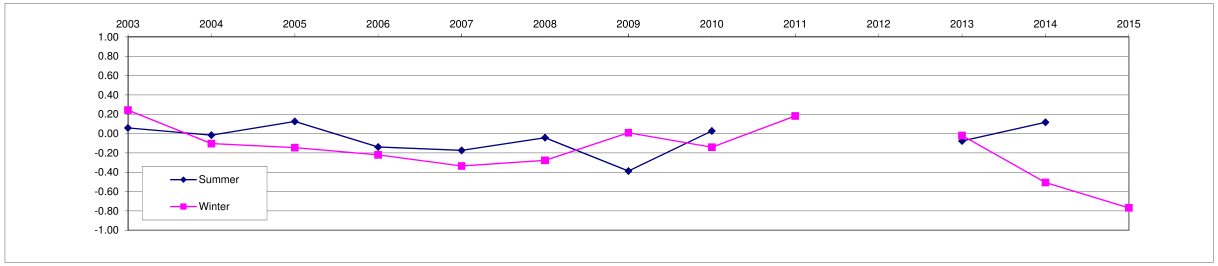






NOTE: Summer goes from July to October Included;
Winter goes from November to June the following year.

Mean Summer error -0.05 m
Max Summer error 0.13 m
Min Summer error -0.39 m



Runoff Calculation Parameters (Location K1b)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0	
Slow flow split	
1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	3,560,000	0.13	9.2
GW	3,560,000	0.13 fracture	

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

Precipitation (mm) - Sheet SMB calcs

Potential evapotranspiration (mm) - Sheet SMB calcs

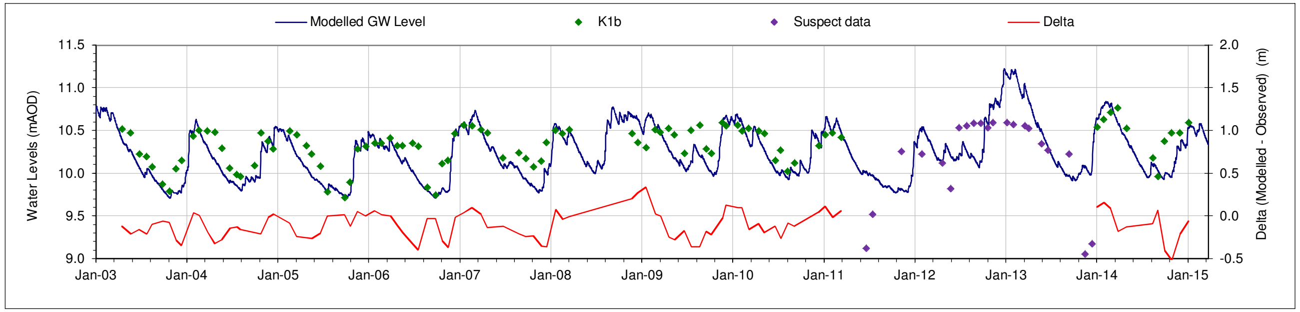
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	95	%
T Slow	150	days
T Fast	150	days
Slow store max	80	mm

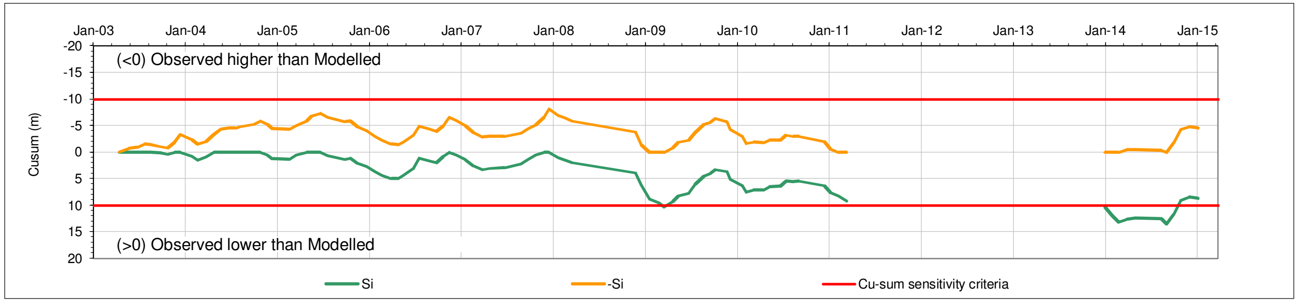
Stats

Baseline dataset for calculation of error statistics:

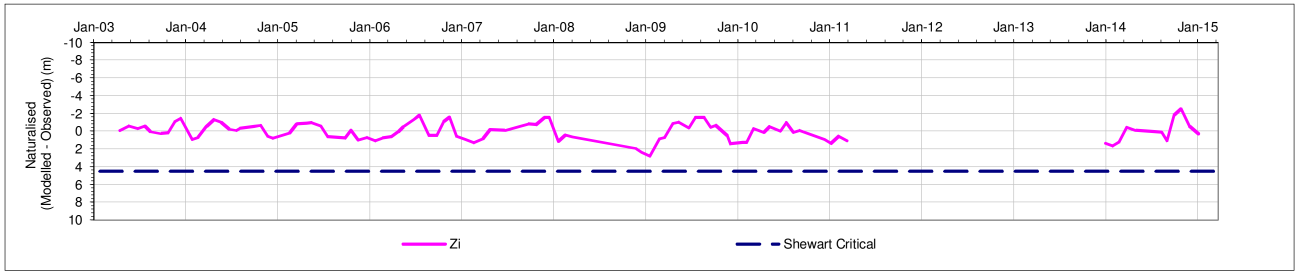
April 2003 - January 2015 (excluding suspect data)

K (not permeability!!)	0.05	m
Mean Error (Modelled - Observed)	-0.10	m
ST Dev Error	0.16	m
Dummy value for Z_i	0	





N.B. The scale on the cusum plot is larger than the CBACs standard (15 m, -15 m)



Runoff Calculation Parameters (Location K2a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	10	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.08	7.3
GW	1,756,799	0.08 fracture	

User-defined time series

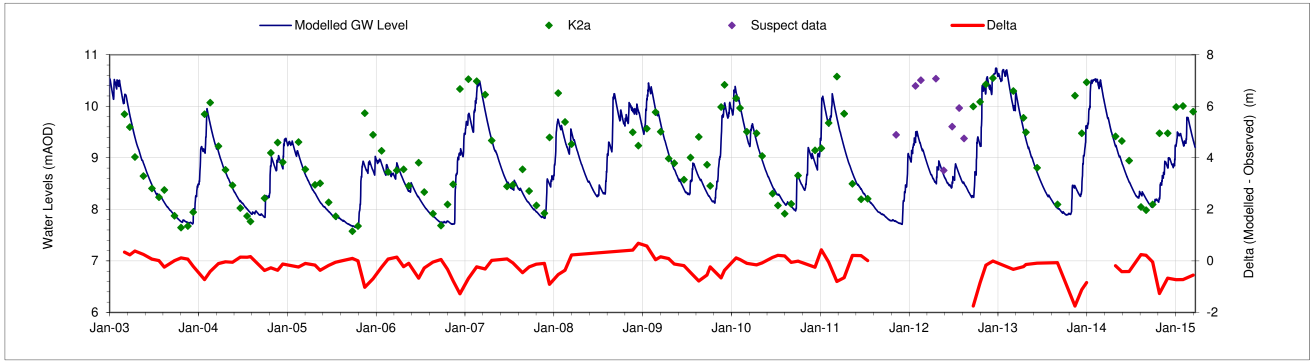
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

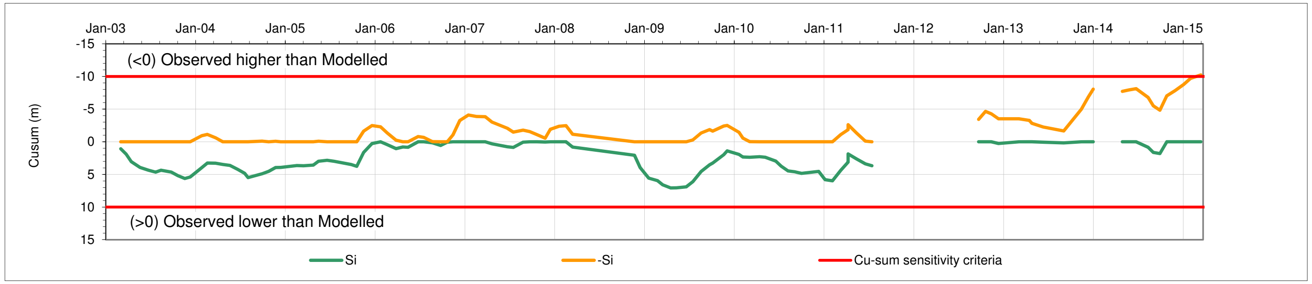
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	110	days
T Fast	110	days
Slow store max	220	mm

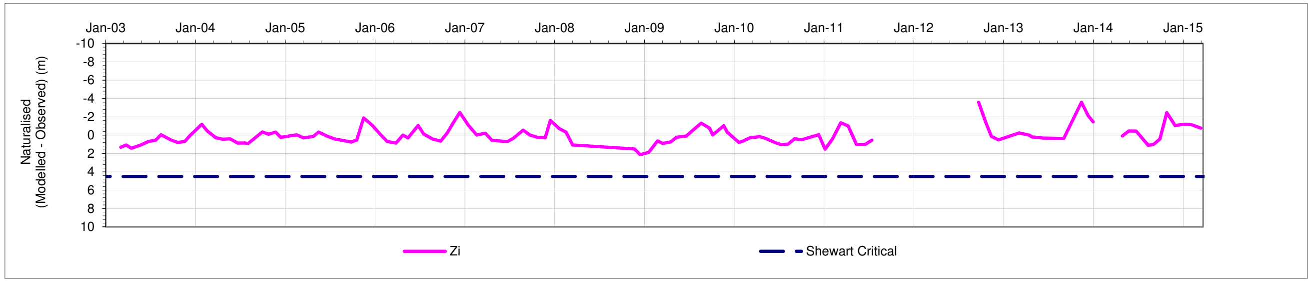
Stats

Baseline dataset for calculation of error statistics:
March 2003 - March 2015 (excluding suspect data)

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.22	m
ST Dev Error	0.43	m
Dummy value for Z_i	0	







Runoff Calculation Parameters (Location K2b)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Kenfig

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	3,560,000	0.05	7.3
GW	3,560,000	0.05 fracture	

User-defined time series

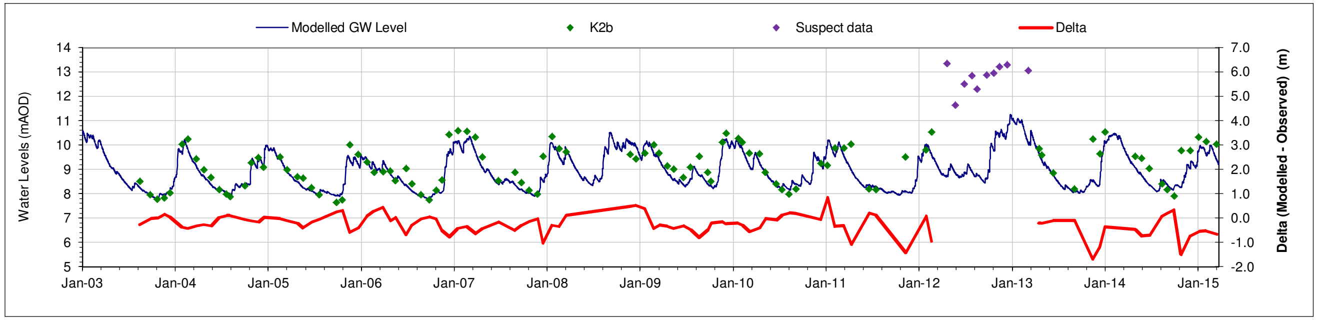
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

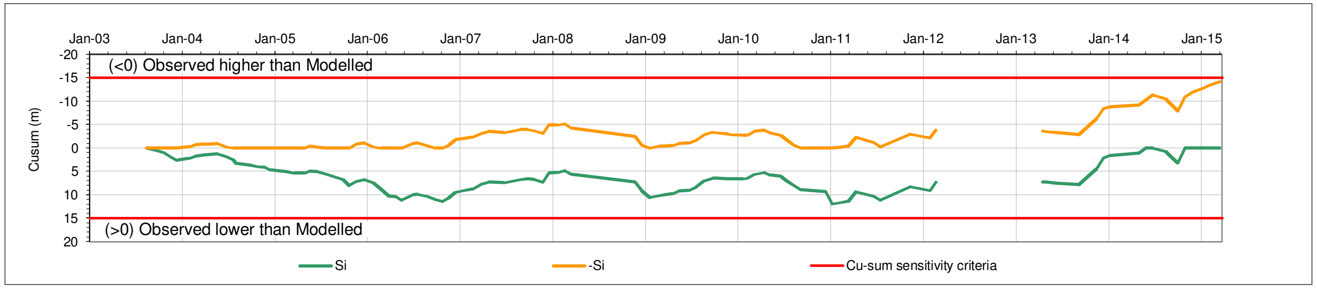
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	85	days
T Fast	85	days
Slow store max	80	mm

Stats

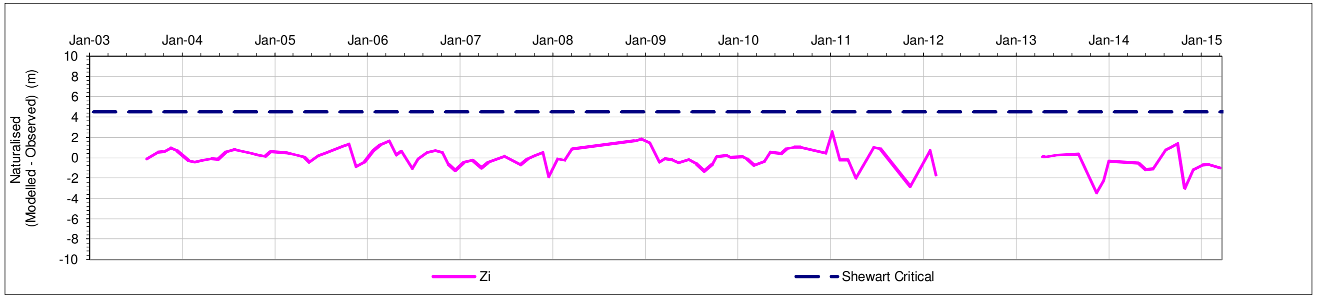
Baseline dataset for calculation of error statistics:
August 2003 - March 2015 (excluding suspect data)

K (not permeability!!)	0.05	m
Mean Error (Modelled - Observed)	-0.24	m
ST Dev Error	0.42	m
Dummy value for Z_i	0	





N.B. The scale on the cusum plot is larger than the CBACS standard (10 m,-10 m)



Runoff Calculation Parameters (Location L)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Schwyll

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.13	10
GW	1,756,799	0.13 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Runoff multiplier	1	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	110	days
T Fast	110	days
Slow store max	100	mm

Stats

Baseline dataset for calculation of error statistics:
May 2001 - June 2013

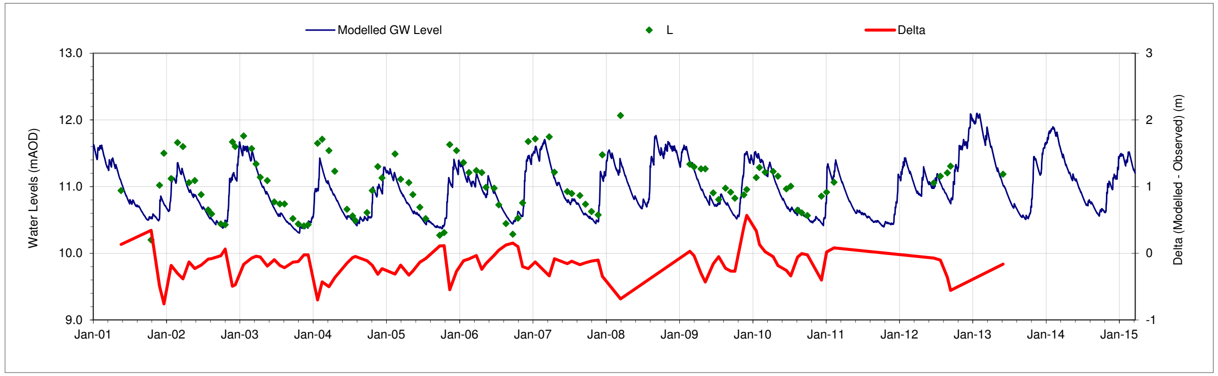
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.15	m
ST Dev Error	0.22	m
Dummy value for Z_i	0	

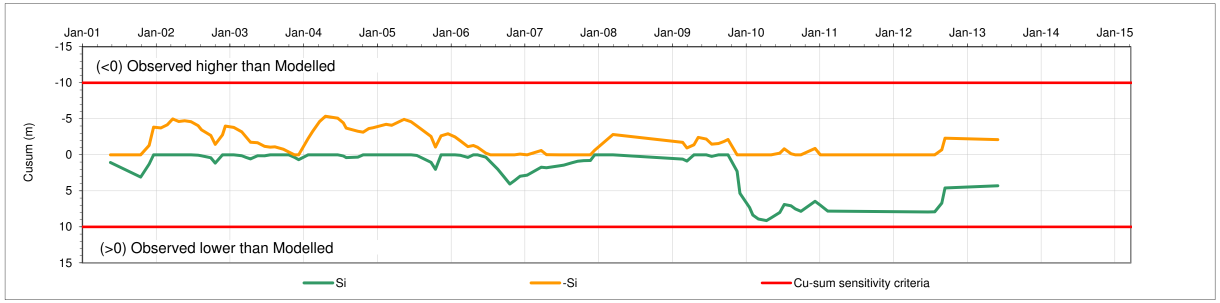
Phi_calibration - last loaded PEST run	n/a
Phi_calibration - spreadsheet calcs	32

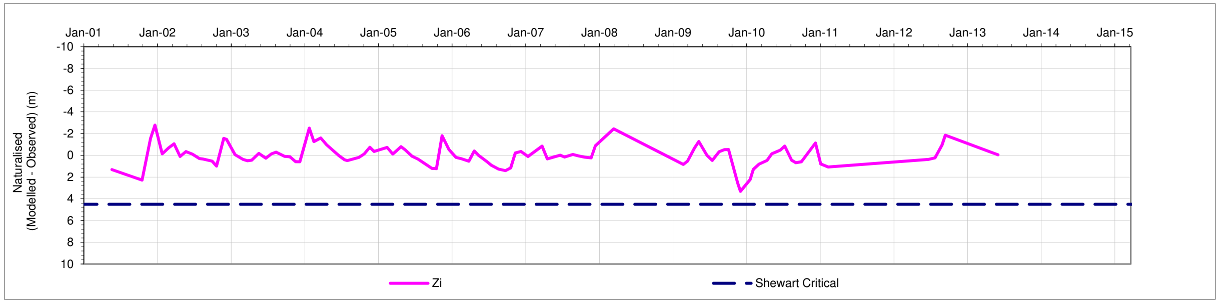
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location N-a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	10	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1756799	0.065	7.5
GW	1756799		

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

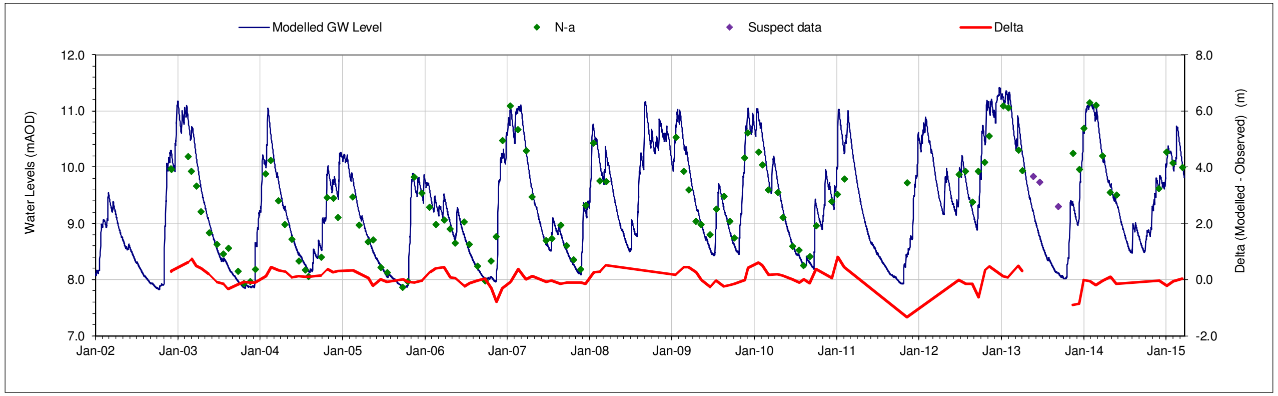
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs
Nb Change cells references on water balance sheet

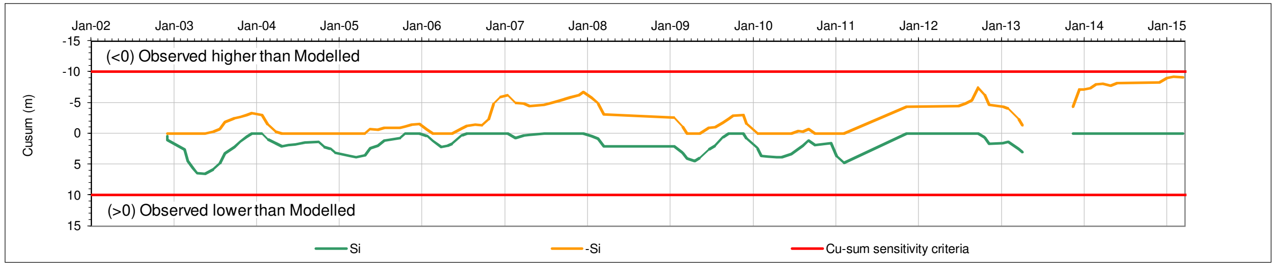
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	90	days
T Fast	90	days
Slow store max	200	mm

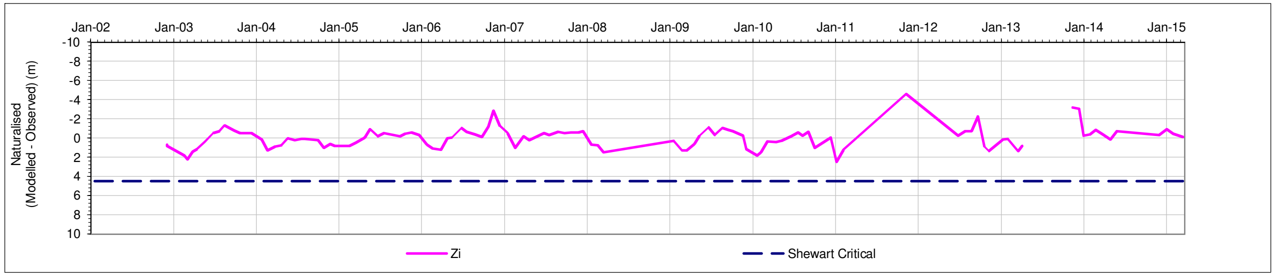
Stats

Baseline dataset for calculation of error statistics:
December 2002 - February 2015 (excluding suspect data)

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	0.08	m
ST Dev Error	0.30	m
Dummy value for Z_i	0	







Runoff Calculation Parameters (Location O-a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
50	20	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall Station: Margam

GW Abstractions (Ml/d) 0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.15	7.2
GW	1,756,799	0.15 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters		
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	80	days
T Fast	80	days
Slow store max	250	mm

Stats

Baseline dataset for calculation of error statistics:
October 2002 - March 2015 (excluding suspect data)

K (not permeability!!) 0.25 m

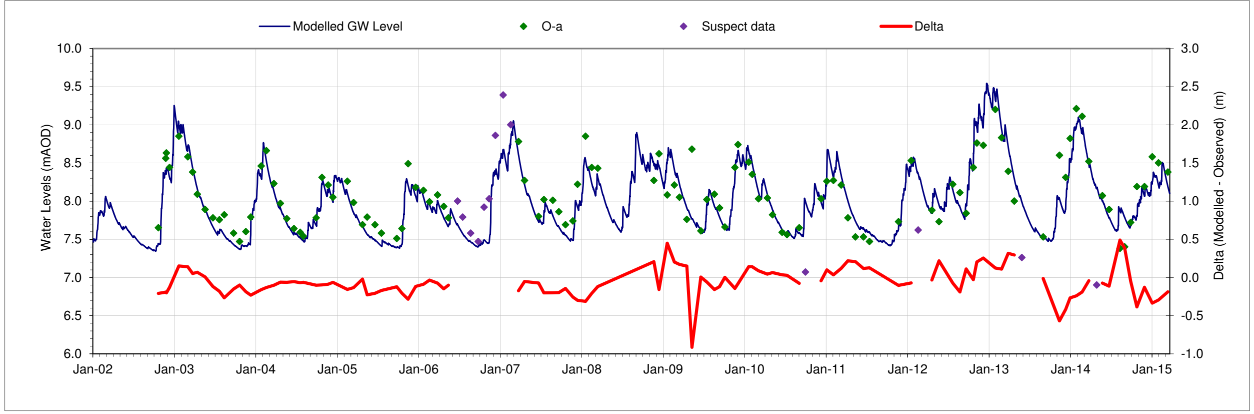
Mean Error (Modelled - Observed)	-0.06	m
ST Dev Error	0.19	m
Dummy value for Z_i	0	

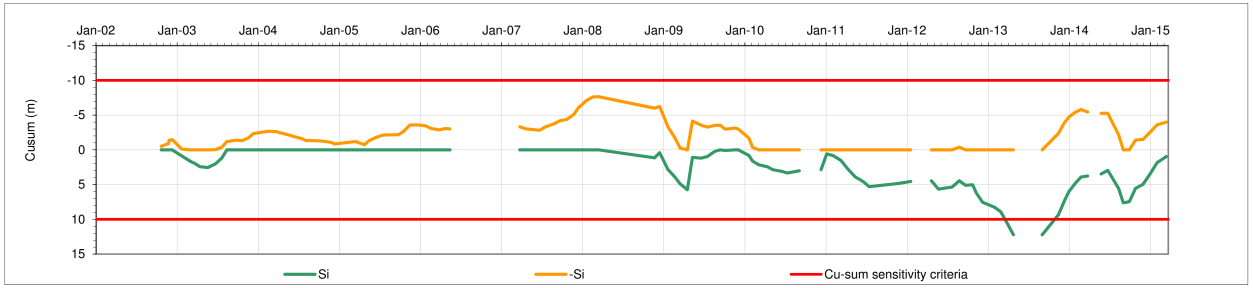
Phi_calibration - last loaded PEST run	n/a
Phi_calibration - spreadsheet calcs	22

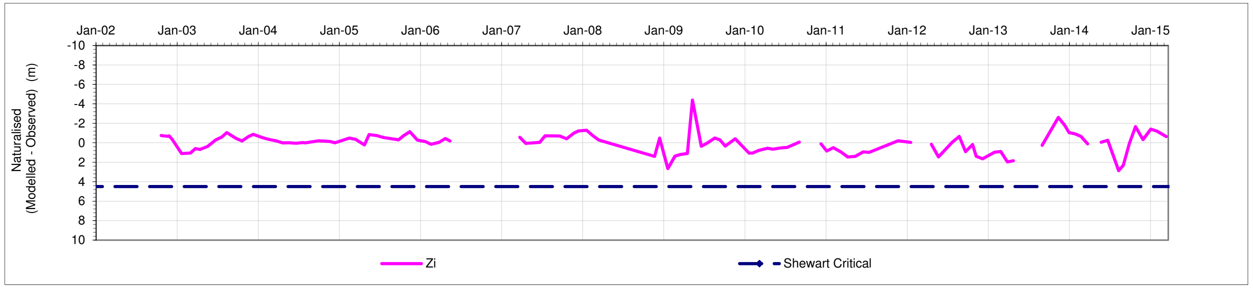
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location P)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.015	12.5
GW	1,420,082	0.015 fracture	

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs
Nb Change cells references on water balance sheet

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	95	%
T Slow	110	days
T Fast	110	days
Slow store max	110	mm

Stats

Baseline dataset for calculation of error statistics:
January 2004 - July 2013

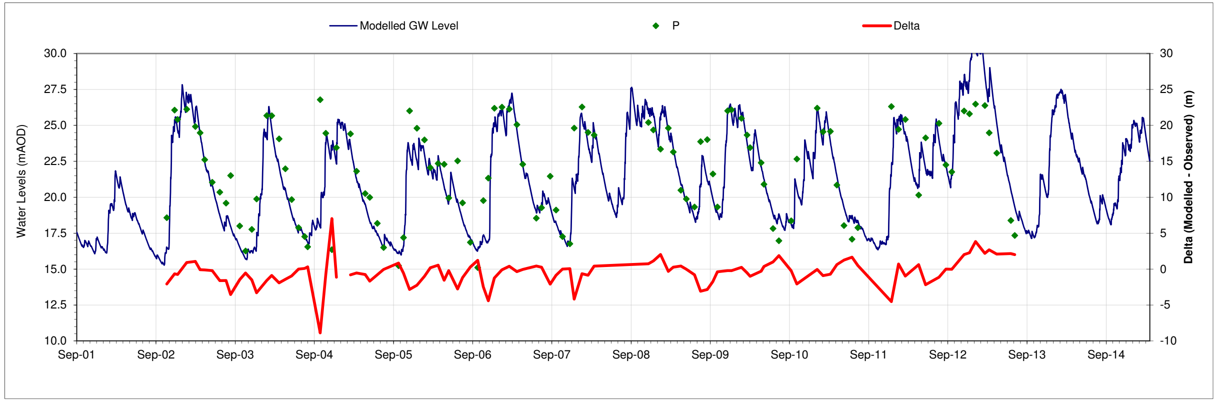
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.26	m
ST Dev Error	1.58	m
Dummy value for Z_i	0	

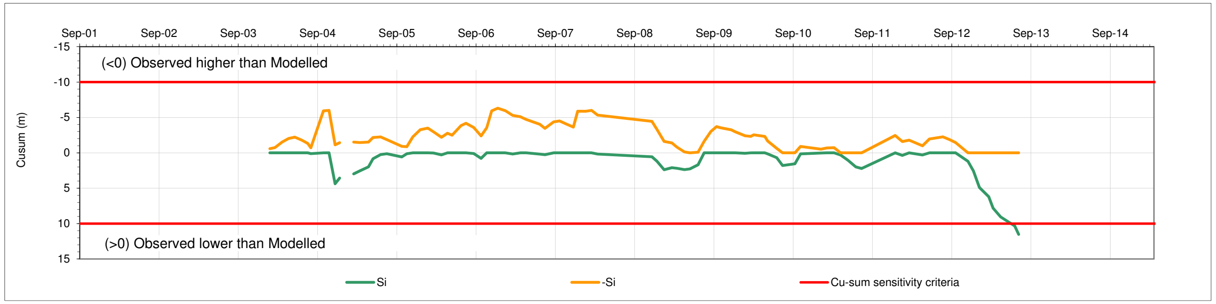
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**2626**

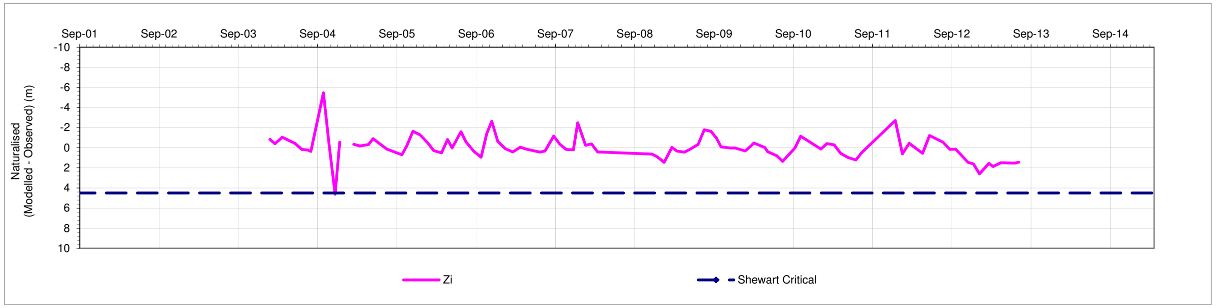
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







O:\6227_Cornelly\calcs\WMP supporting calcs\CBAC spreadsheets\P_new store 2015.xlsm Parameters

05/08/2015 14:07

Runoff Calculation Parameters (Location Q)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	5	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.008	21
GW	1,420,082	0.008 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs
Nb Change cells references on water balance sheet

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	90	%
T Slow	83	days
T Fast	83	days
Slow store max	200	mm

Stats

Baseline dataset for calculation of error statistics:
October 2002 - May 2013

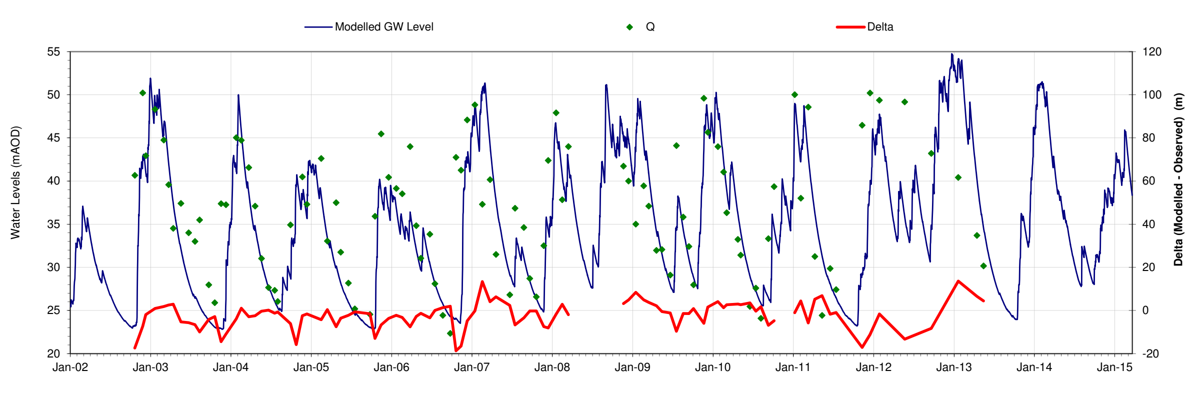
K (not permeability!!)	0.2	m
Mean Error (Modelled - Observed)	-2.15	m
ST Dev Error	6.10	m
Dummy value for Z_i	0	

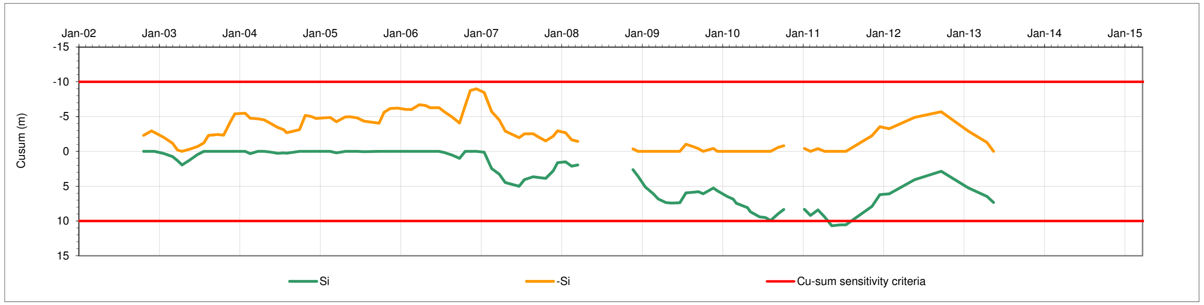
Phi_calibration - last loaded PEST run	n/a
Phi_calibration - spreadsheet calcs	#N/A

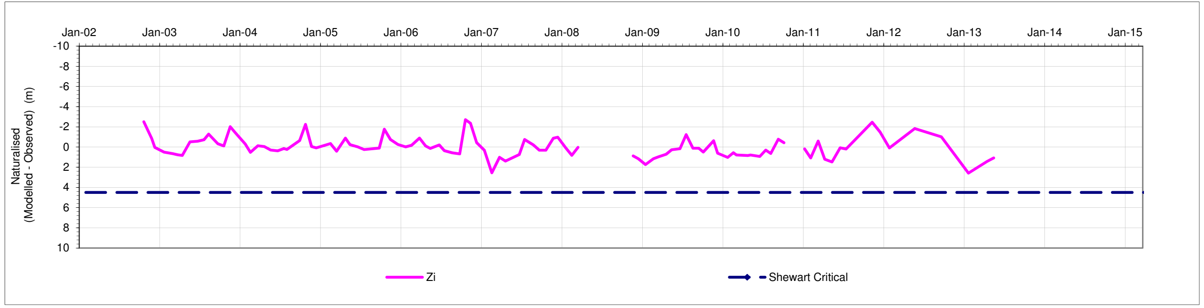
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Cornelly Quarry Pumping)

N.B. Pumping rates used are average fortnightly rates out of Cornelly floor (m3/d)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	3,800,000	0.004	30
GW	3,800,000	0.004	

Rainfall Multiplier	1
PE Multiplier	1
Runoff multiplier	1

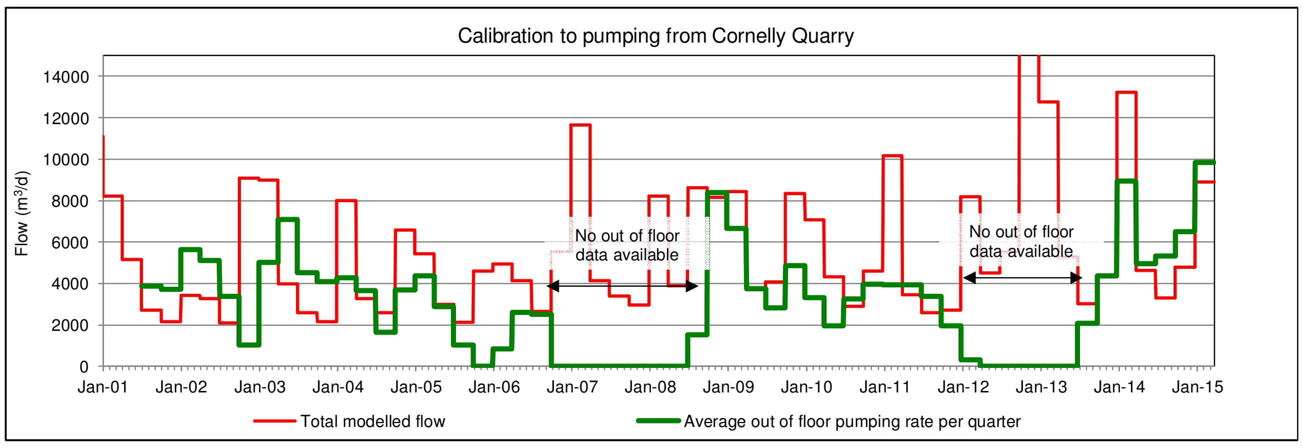
User-defined time series

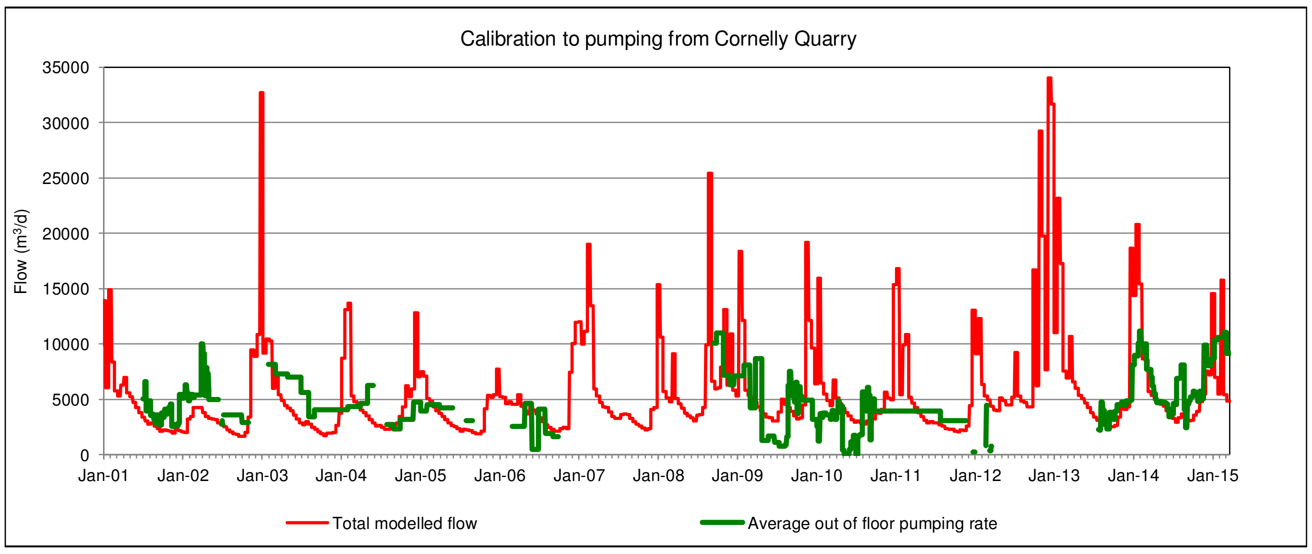
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

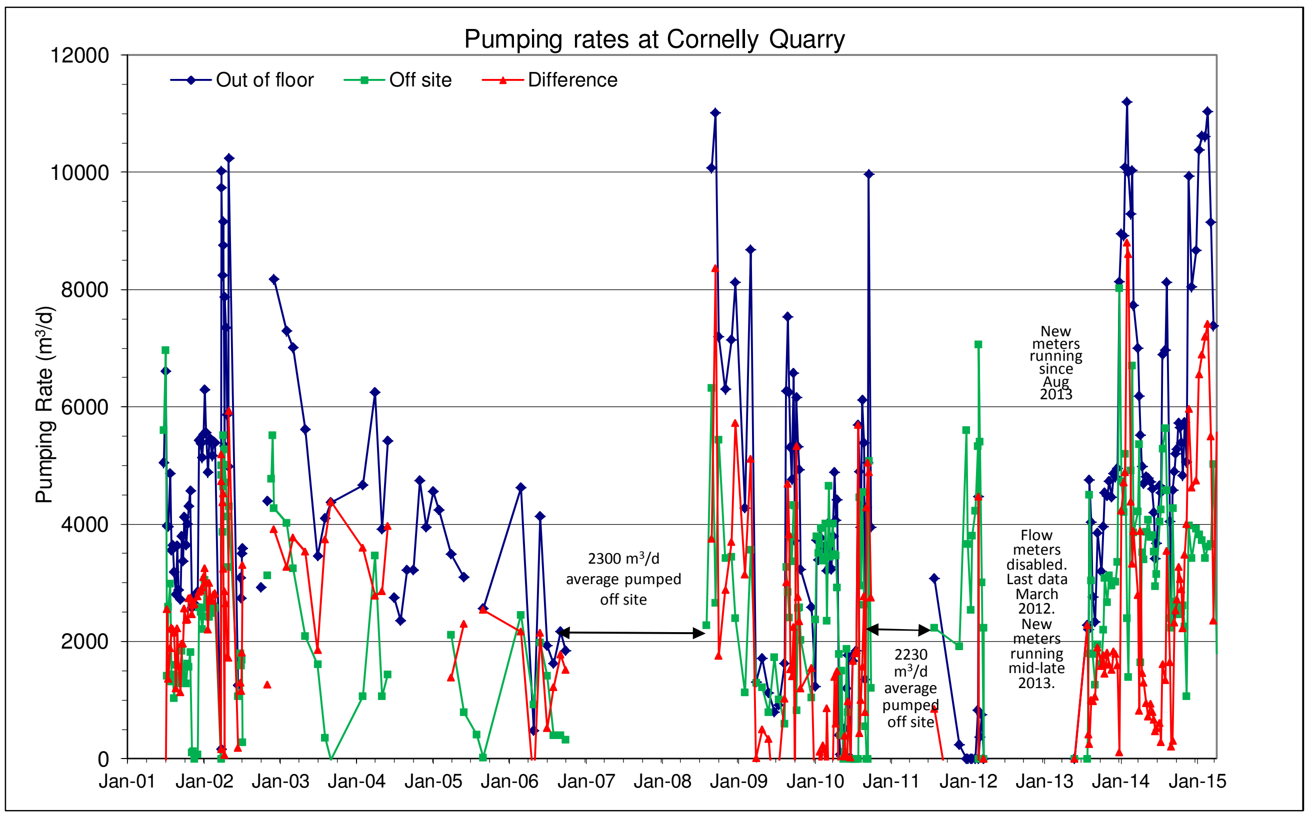
Parameter	Value	Unit
% Slow	95	%
Fast_store_Starting_Volume	0	mm
Slow_store_Starting_Volume	0	mm
GW_Abstractions__Ml_d	0	Ml/d
Slow_flow_split	1	-
Slow_store_max	90	mm
TFast	120	days
TSlow	120	days

LTA quarry pumping rate *January 1986 - April 2015*	5948.68	m3/d
Actual average quarry pumping rate *August 2013 - April 2015*	6317.57	m3/d





N.B. The pumping rates at Cornelly Quarry graph provides an indication of gaps in the data record



Runoff Calculation Parameters (Location R-a)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d) 0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

Rainfall Multiplier 1
PE Multiplier 1

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield		Starting_Head (mAOD)
SW	1,756,799	0.15		7.4
GW	1,756,799	0.15	fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters		
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	65	days
T Fast	65	days
Slow store max	250	mm

Stats

Baseline dataset for calculation of error statistics:
October 2002 - March 2015 (excluding suspect data)

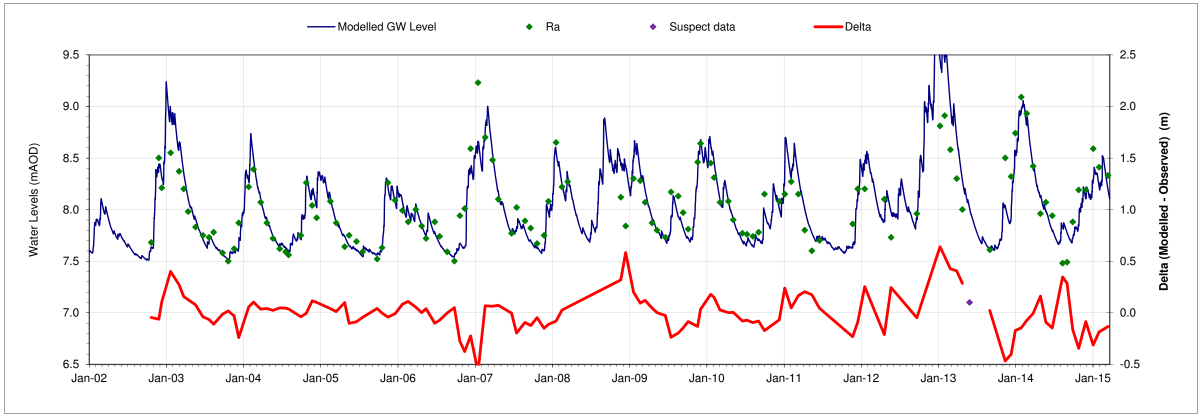
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	0.01	m
ST Dev Error	0.19	m
Dummy value for Z_i	0	

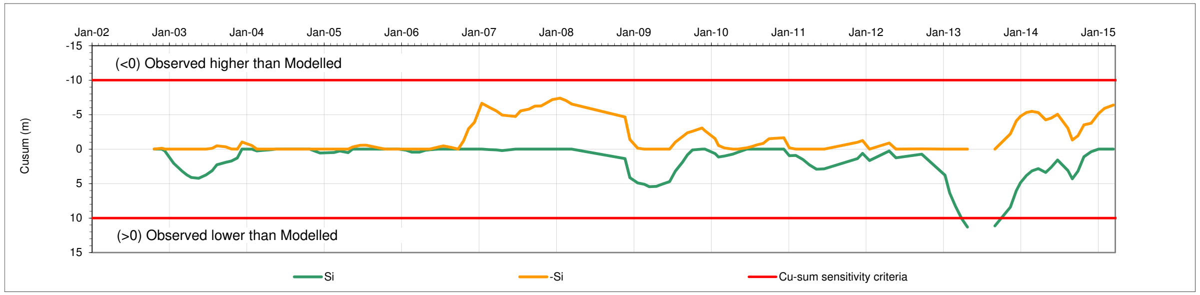
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**26**

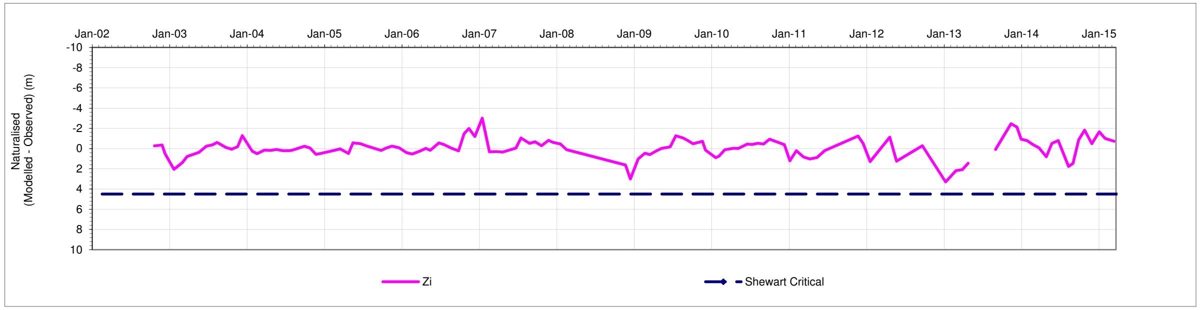
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location RWC105)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

Rainfall Multiplier 1
PE Multiplier 1

GW Abstractions (Ml/d) 0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.012	11
GW	1,420,082	0.012 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	80	days
T Fast	80	days
Slow store max	150	mm

Stats

Baseline dataset for calculation of error statistics:
January 2003 - March 2015

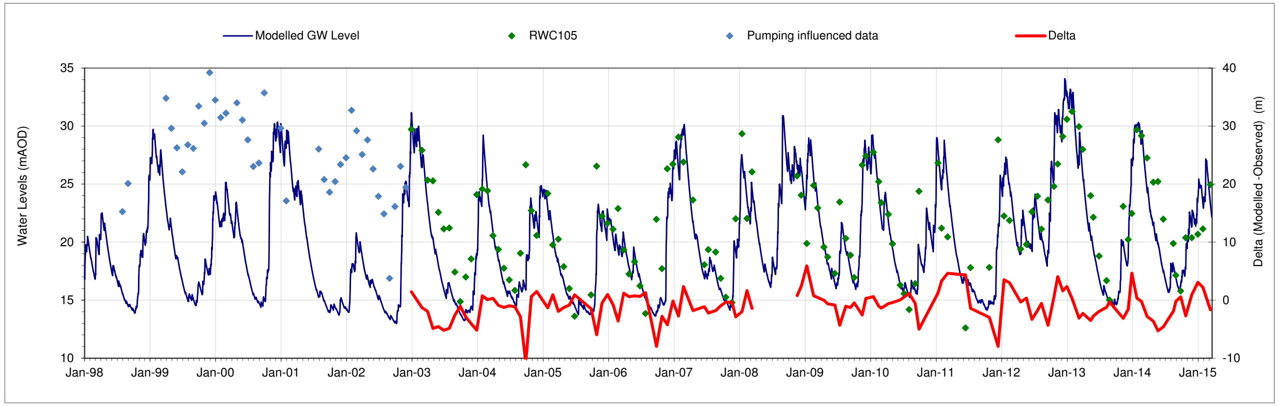
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-0.98	m
ST Dev Error	2.63	m
Dummy value for Z_i	0	

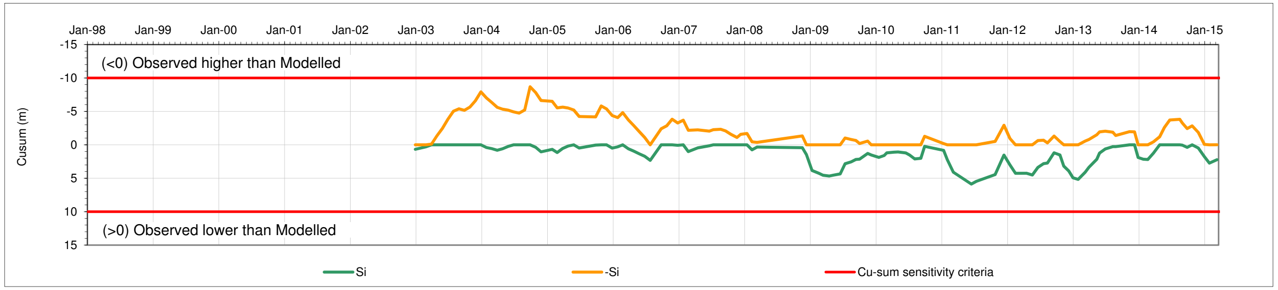
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**22586**

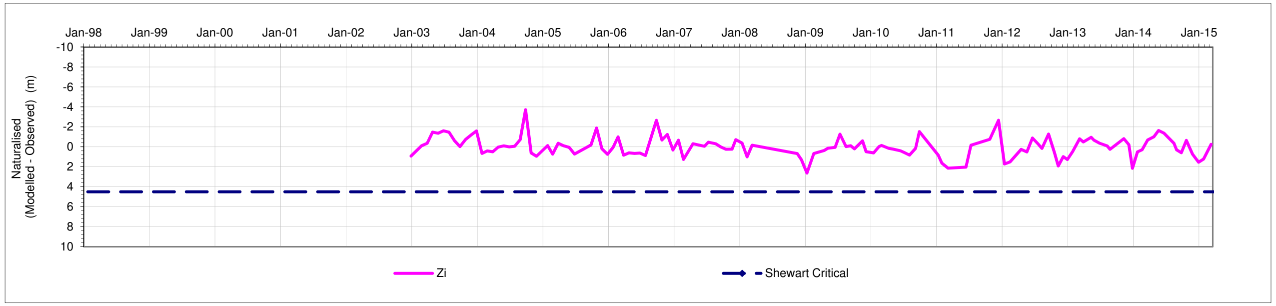
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	







Runoff Calculation Parameters (Location RWC106)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.012	10
GW	1,420,082	0.012 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	80	days
T Fast	80	days
Slow store max	150	mm

Stats

Baseline dataset for calculation of error statistics:
January 2003 - March 2015 (excluding suspect data)

K (not permeability!!) 0.25 m

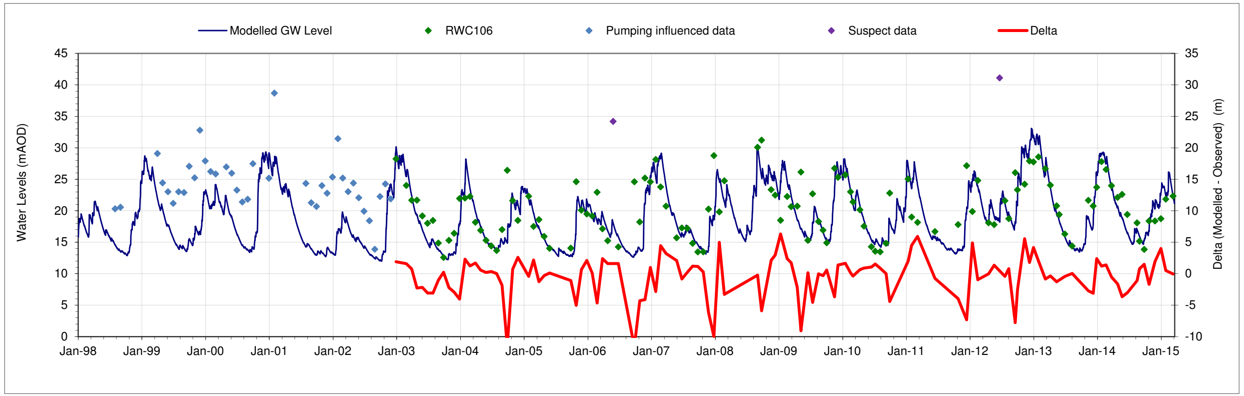
Mean Error (modelled - Actual) -0.43 m
ST Dev Error 3.25 m
Dummy value for Z_i 0

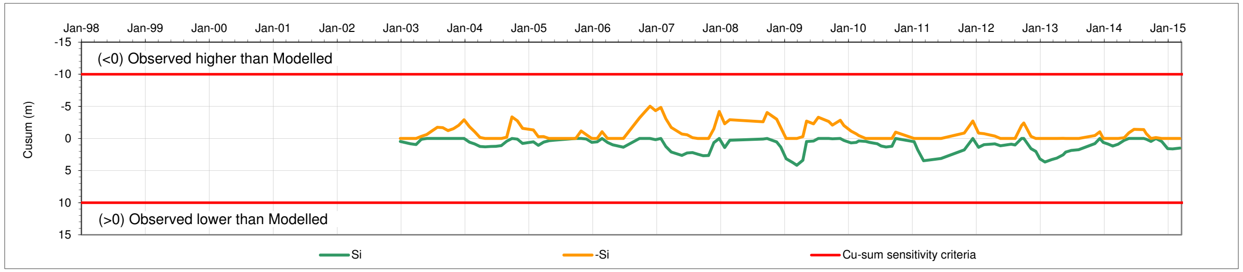
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**4949**

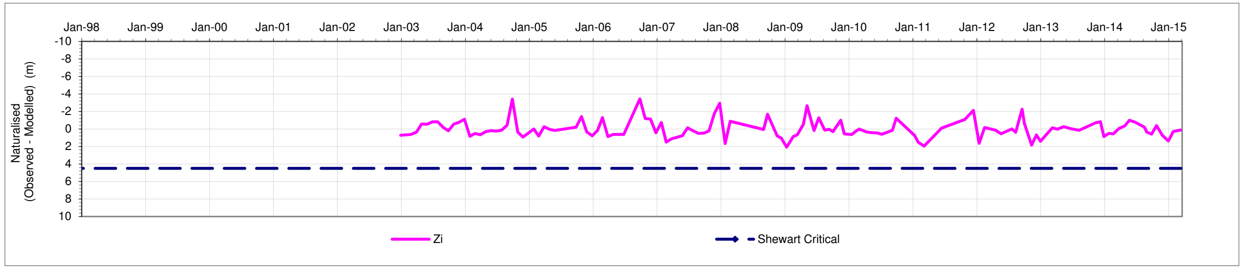
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

PEST weightings

Default weight for minimum annual values 20.0
Default weight for maximum annual values 10.0
Default standard weight is 1.0







Runoff Calculation Parameters (Location South Cornelly)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.018	9.5
GW	1,756,799	0.018 fracture	

User-defined time series
Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters		
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	70	days
T Fast	70	days
Slow store max	160	mm

Stats

Baseline dataset for calculation of error statistics:
September 2002 - January 2013

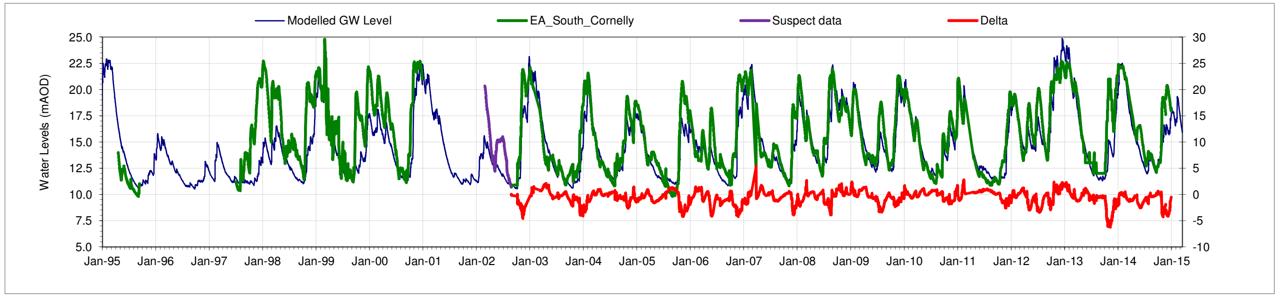
K (not permeability!!)	0.25	m
Mean Error (modelled - Actual)	-0.51	m
ST Dev Error	1.24	m
Dummy value for Z_i	0	

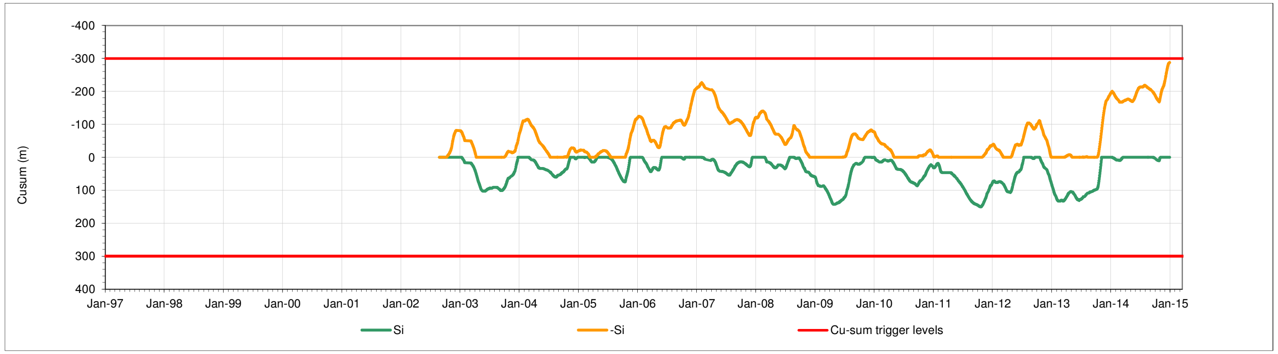
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**27022**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

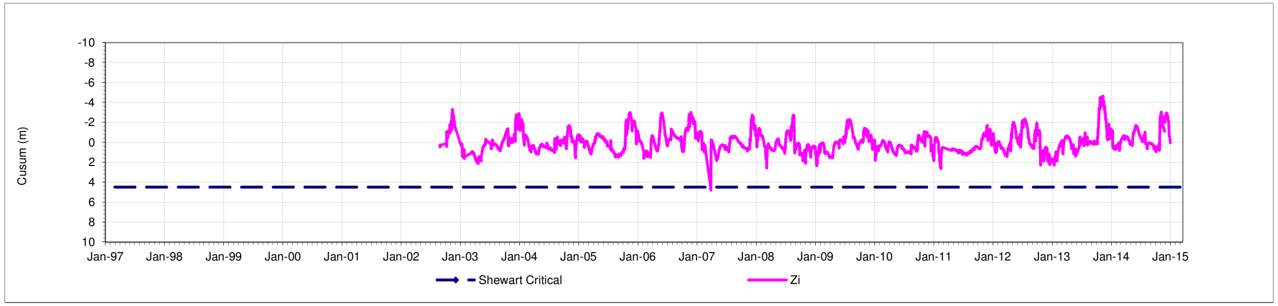
PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	





N.B. The scale on the cusum plot is larger than the CBACs standard (10 m, -10 m)



Runoff Calculation Parameters (Location T95/01)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0.01	0.01	0.01
20	0.01	0.01	0.01

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters **Head Change Calculation**

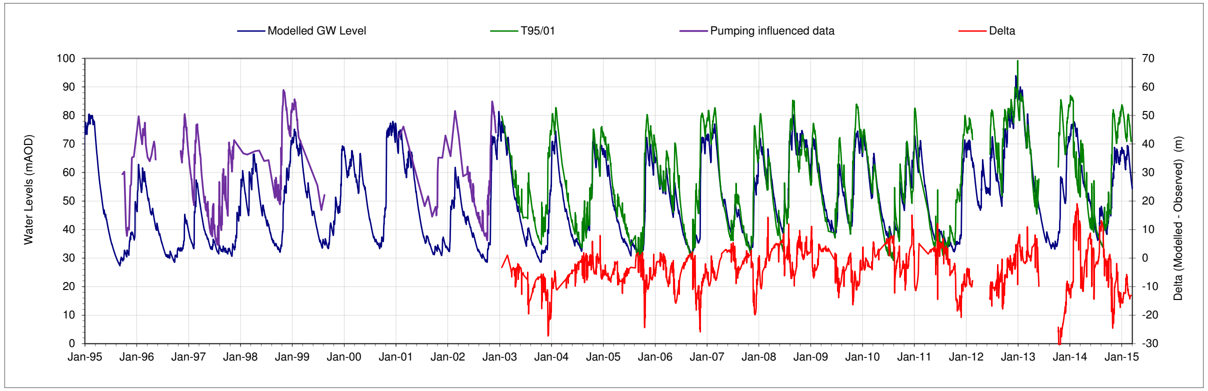
	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1420082	0.0028	20
GW	1420082	0.0028 fracture	

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs
Nb Change cells references on water balance sheet

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	80	days
T Fast	80	days
Slow store max	80	mm



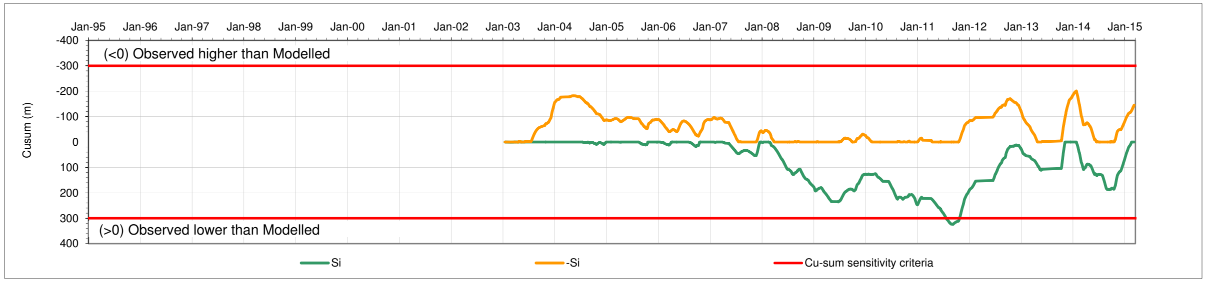
Stats

Baseline dataset for calculation of error statistics:
January 2003 - March 2015

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	-3.77	m
ST Dev Error	6.93	m
Dummy value for Z_i	0	

Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**257497**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

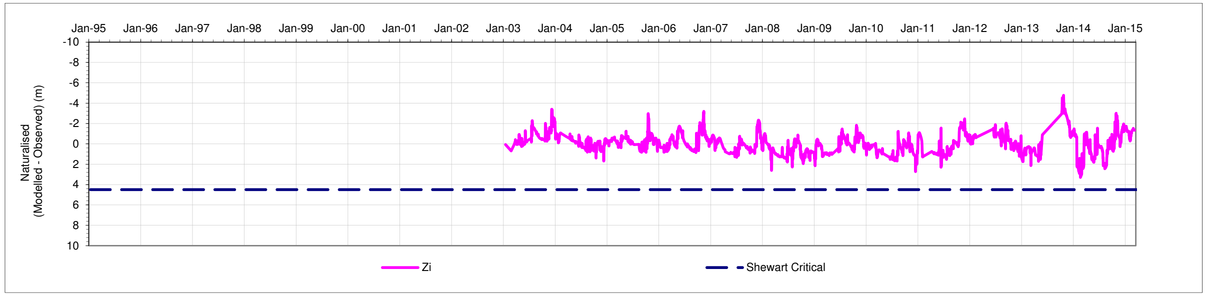


PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0

Default standard weight is 1.0

N.B The scale on this cusum plot is larger than the CBACs standard (10 m, -10 m)



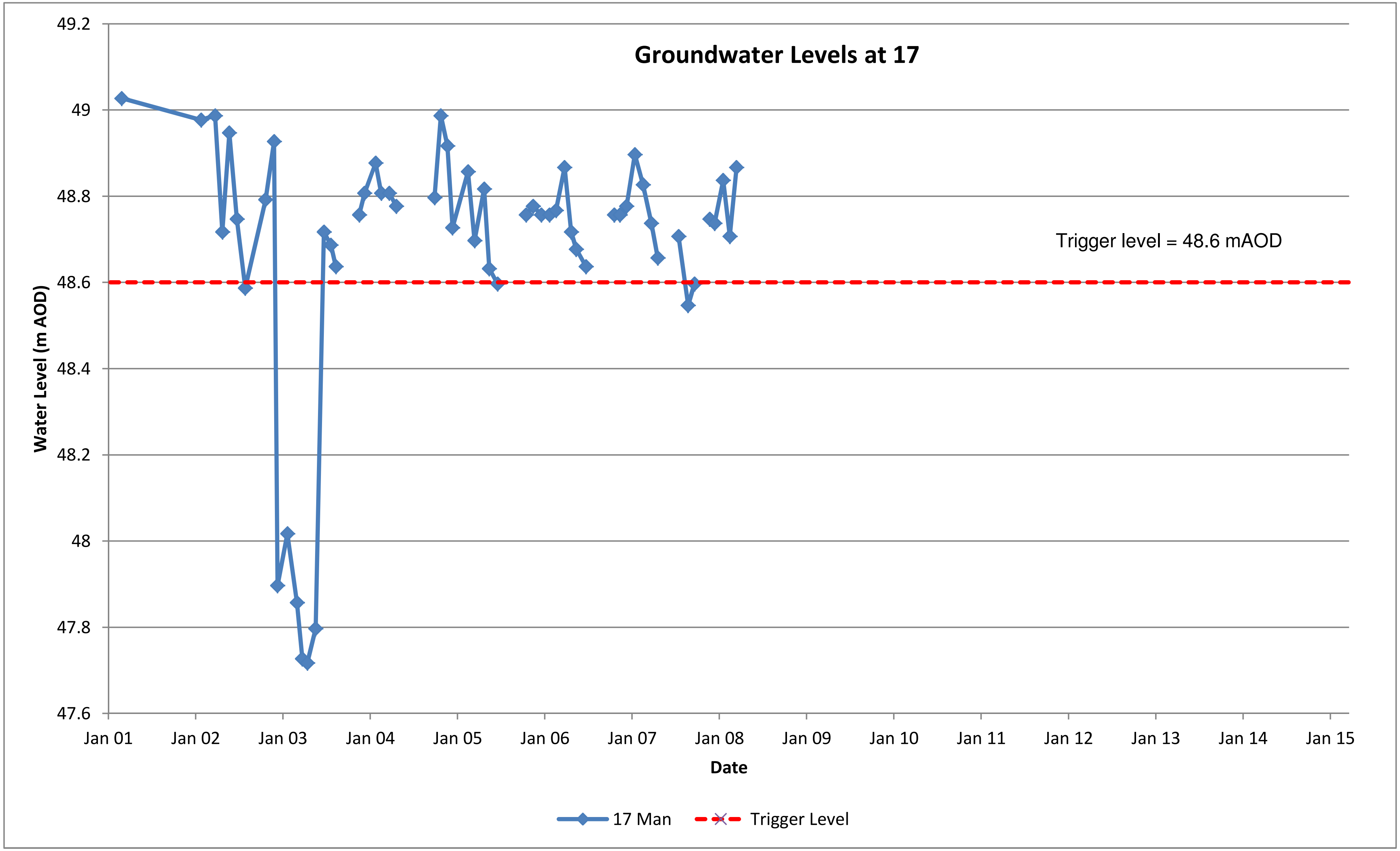


Figure H.1

Groundwater levels at 17 (north of Cornelly Quarry) and trigger level

Date	Drawn
Jun-15	KHB
Scale	Checked
dns	BCH
Original	Revision
A4	1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.1 17.xlsx]H1

Environment Specialists

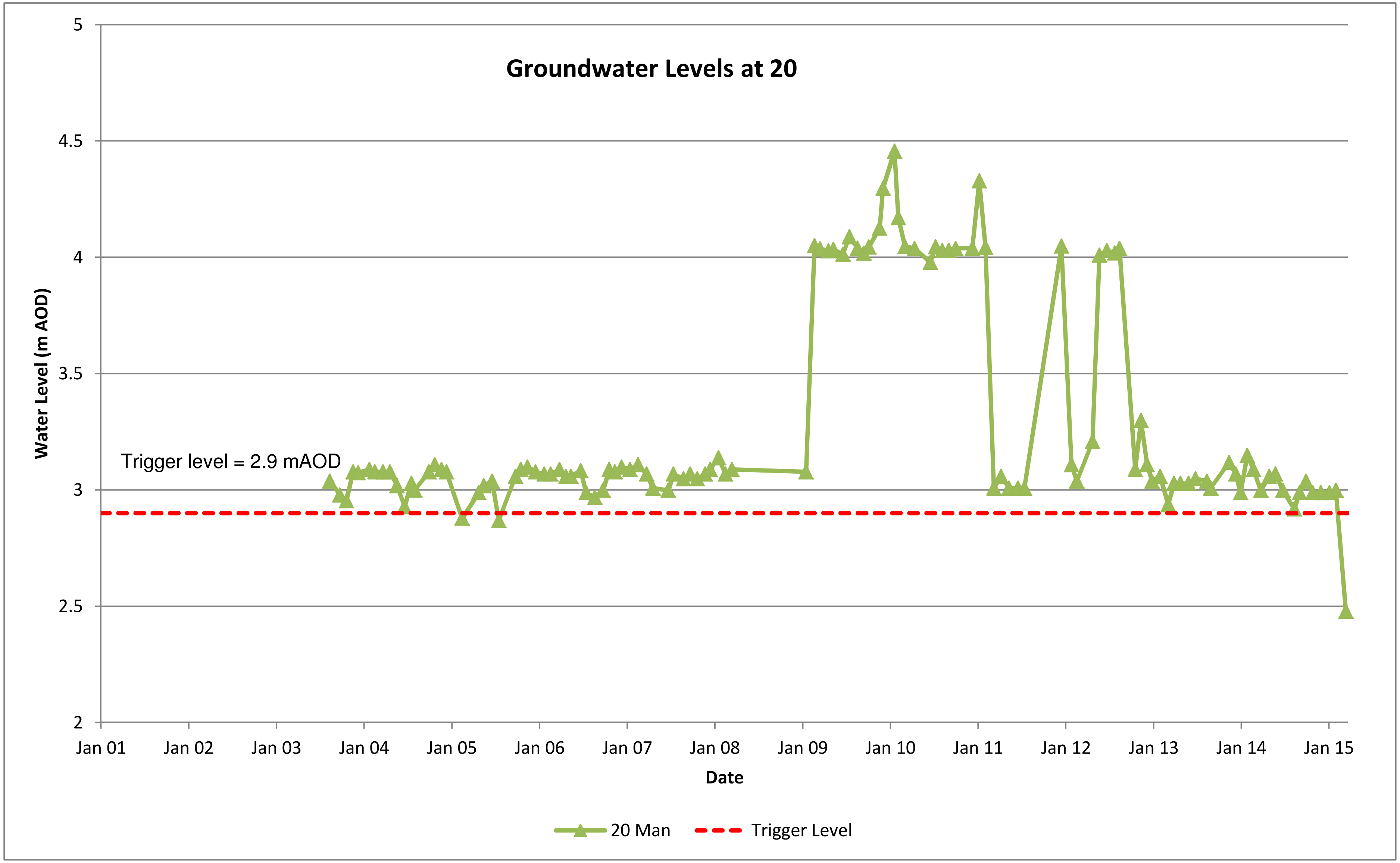


Figure H.2

Groundwater levels at 20 (Porth Cawl) and trigger level

Date Jun-15	Drawn KHB
Scale dns	Checked BCH
Original A4	Revision 1
File Reference O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.2.xlsx]H2	

Environment Specialists

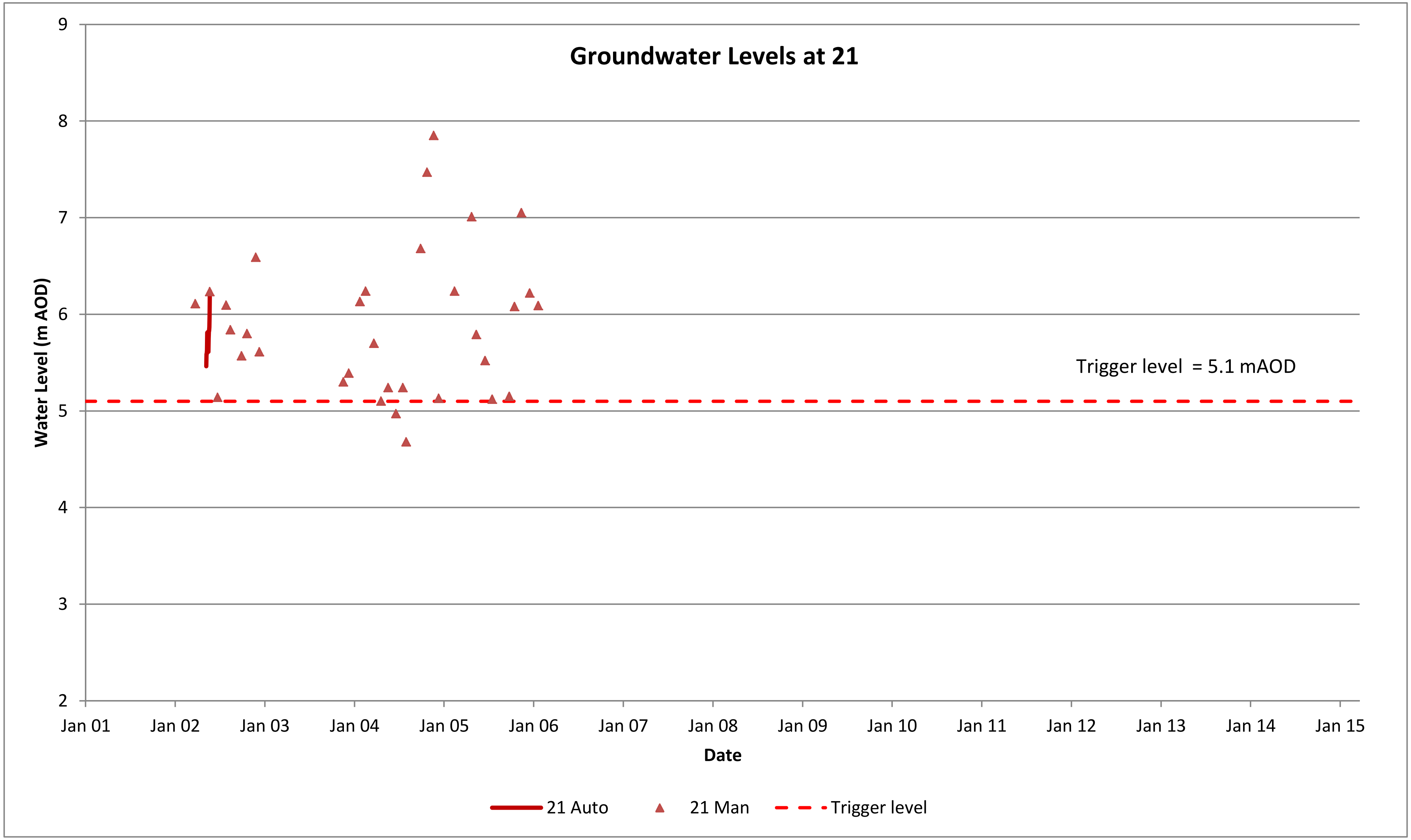


Figure H.3

Groundwater levels at 21 (Porth Cawl)

Date Jun-15	Drawn KHB
Scale dns	Checked BCH
Original A4	Revision 1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.1 17.xlsx]H1

esi Environment Specialists

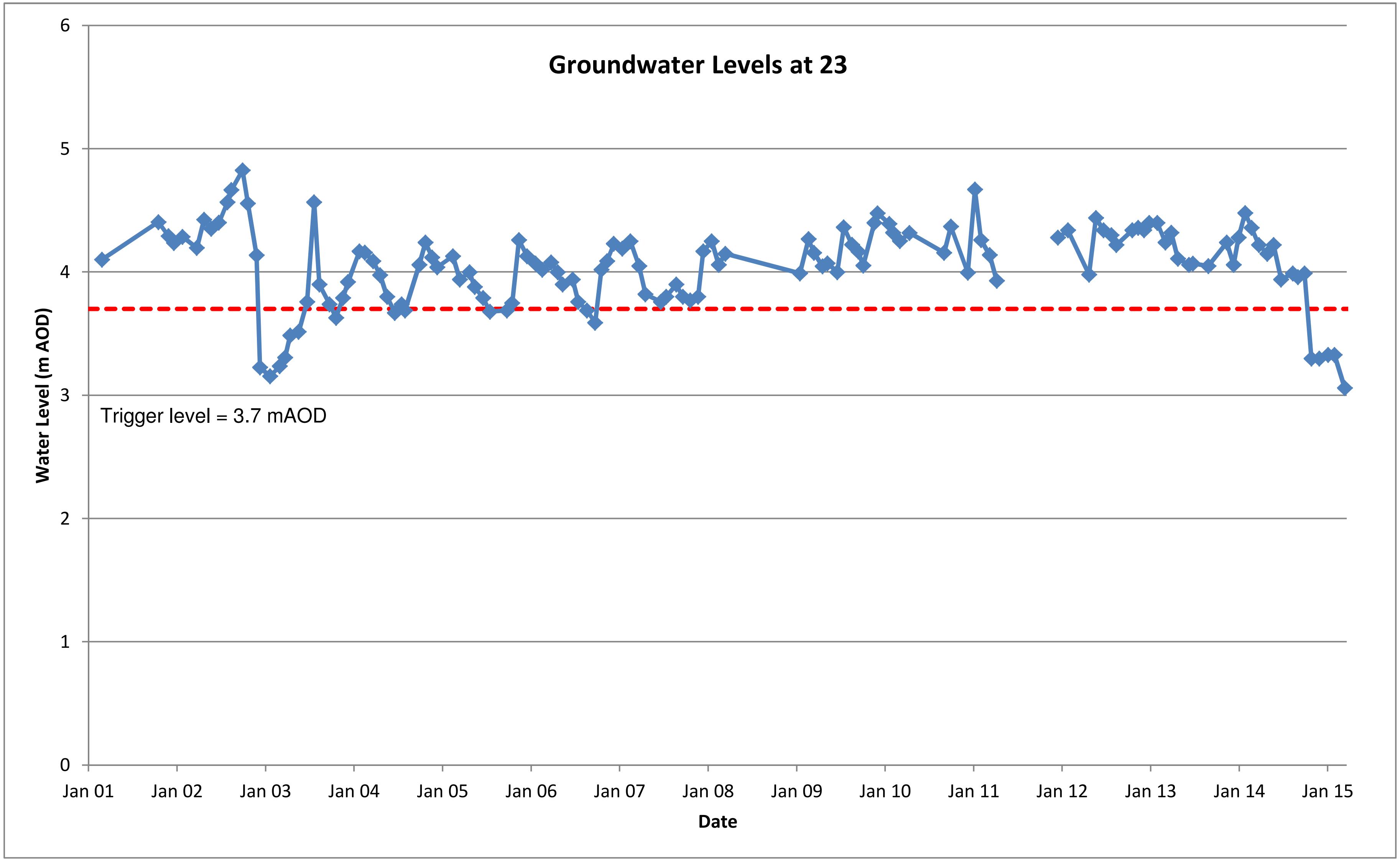


Figure H.4

Groundwater levels at 23 (Porth Cawl) and trigger level

Date	Jun-15	Drawn	KHB
Scale	dns	Checked	BCH
Original	A4	Revision	1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.4.xlsx]H4

esi Environment Specialists

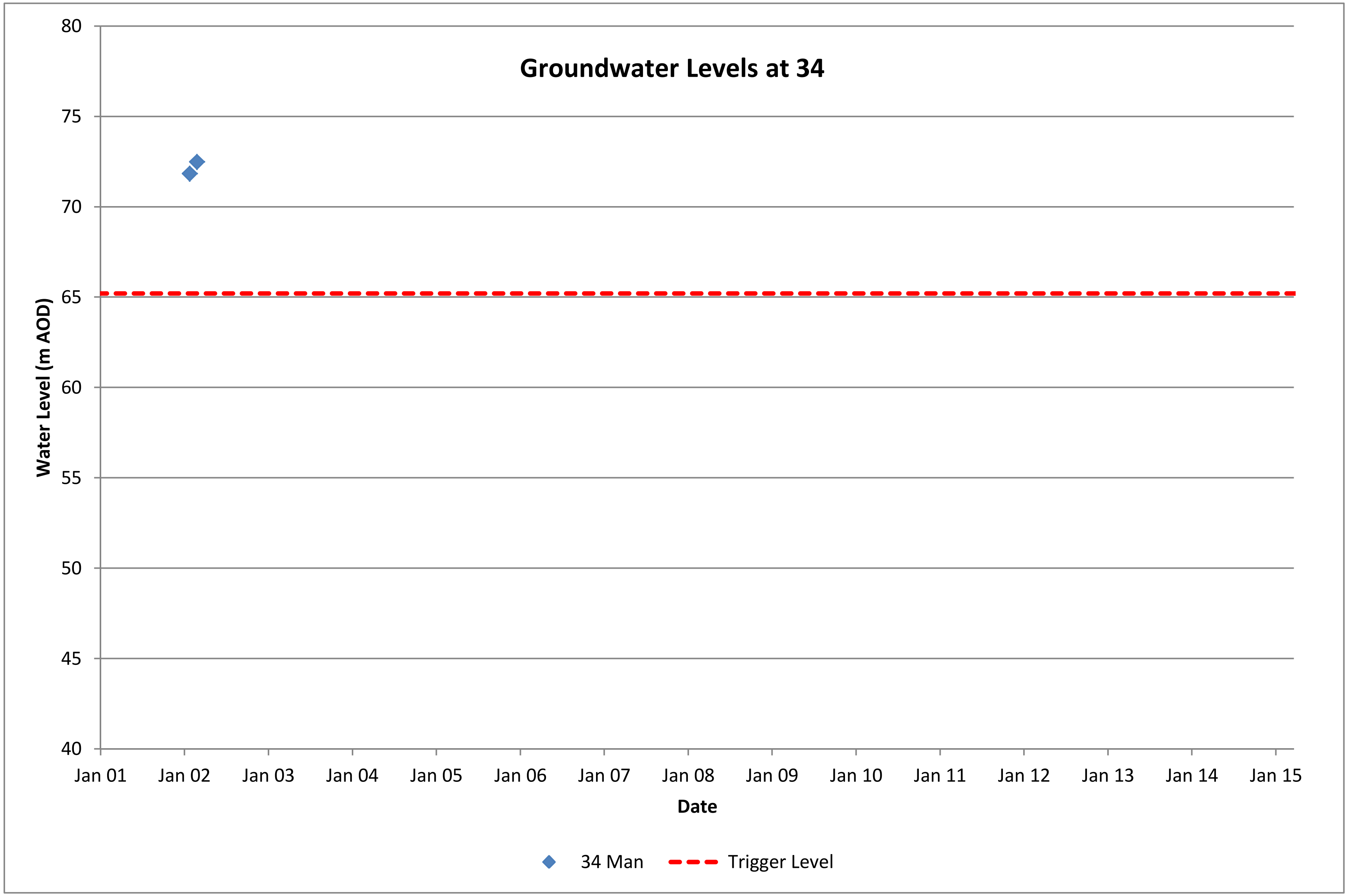


Figure H.5

Groundwater levels at 34 (Tythegston landfill) and trigger level

Date	Drawn
Jun-15	KHB
Scale: dns	Checked: BCH
Original: A4	Revision: 1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.5.xlsx]H5

esi Environment Specialists

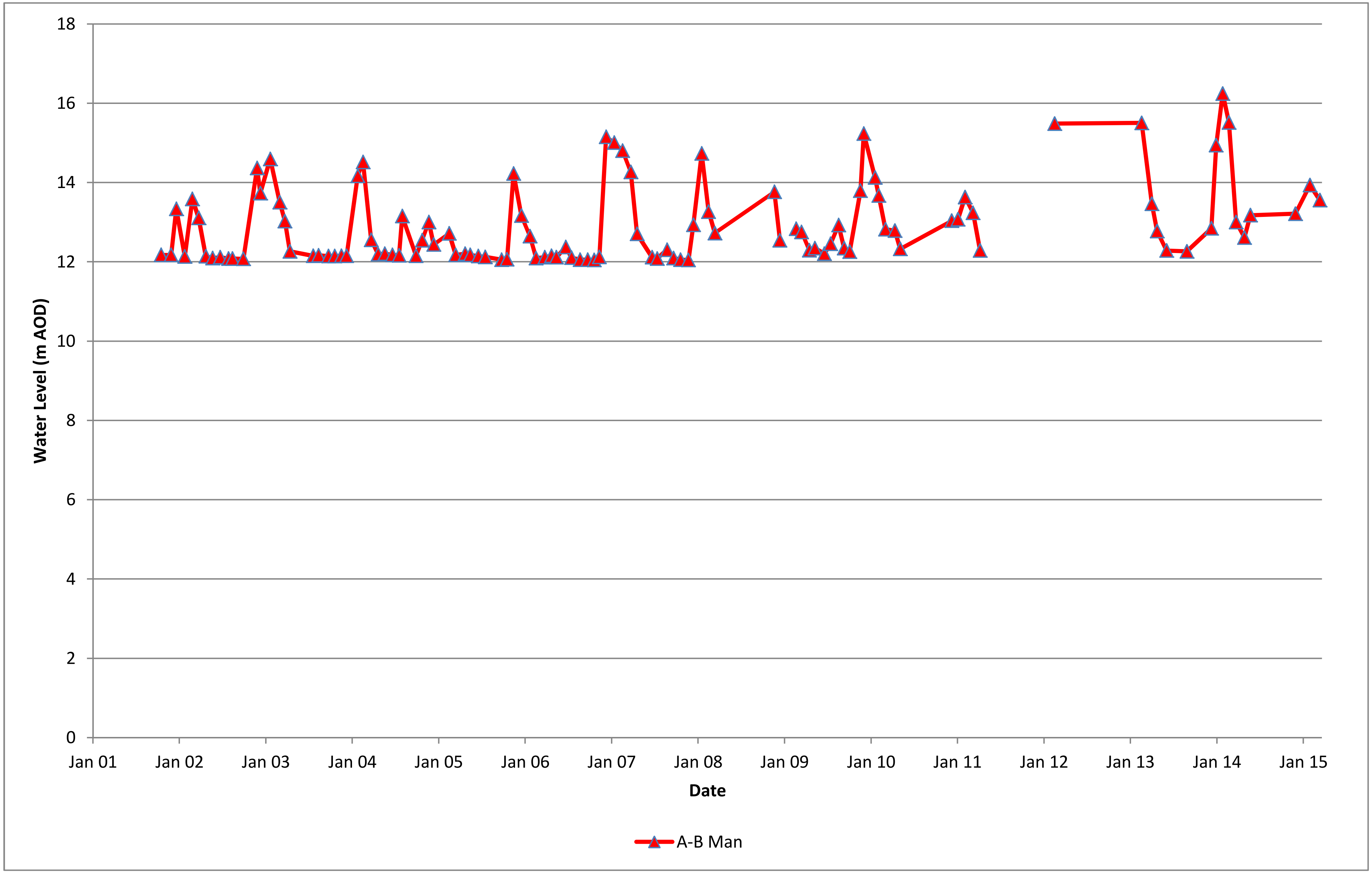


Figure H.6

Groundwater levels at A-b (Kenfig Pool)

Date Jun-15	Drawn KHB
Scale dns	Checked BCH
Original A4	Revision 1
File Reference O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.6.xlsx]H6	

esi Environment Specialists

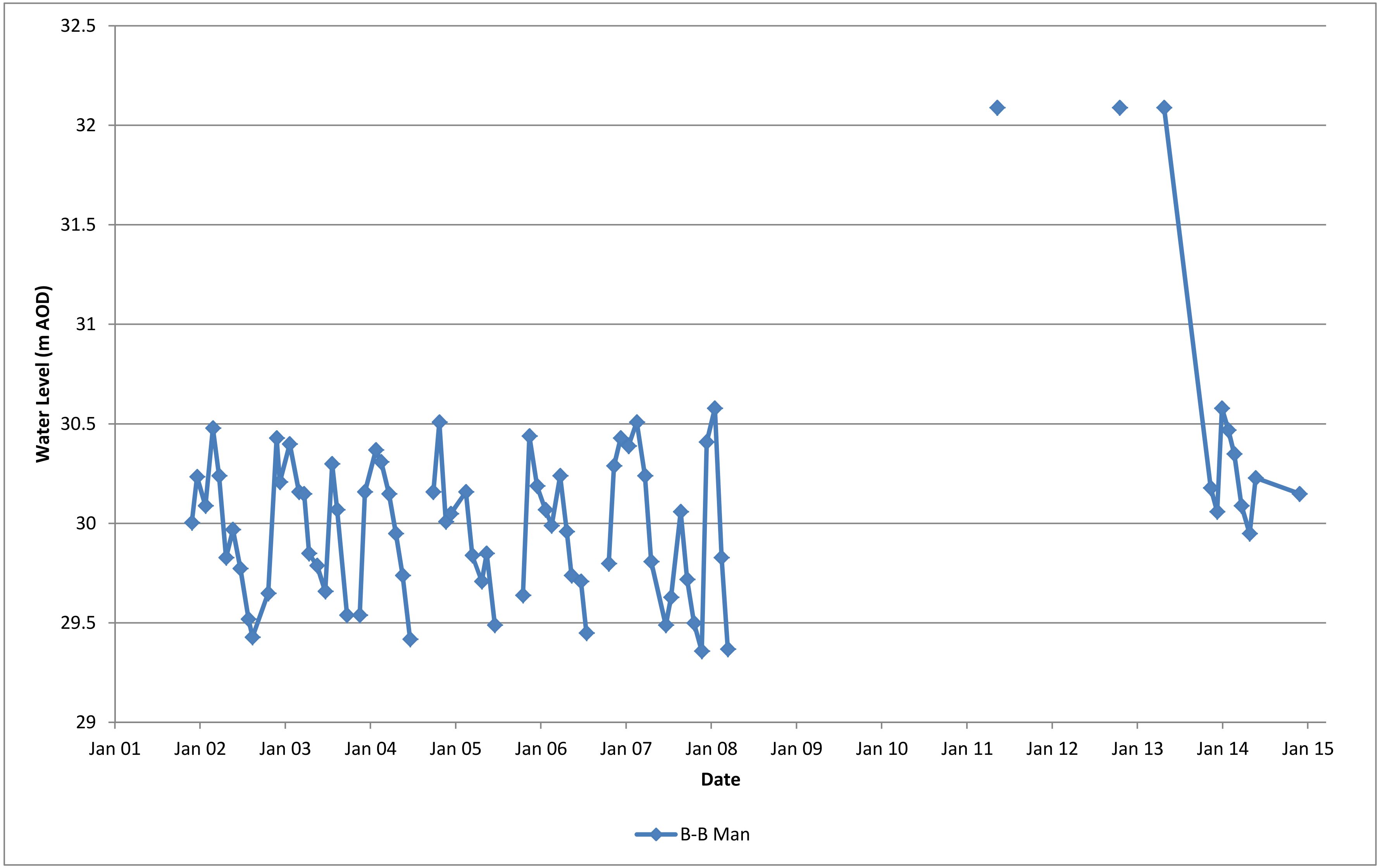


Figure H.7

Groundwater levels at B-b (Sker)

Date	Drawn
Jun-15	KHB
Scale dns	Checked BCH
Original A4	Revision 1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.7.xlsx]Data

Environment Specialists

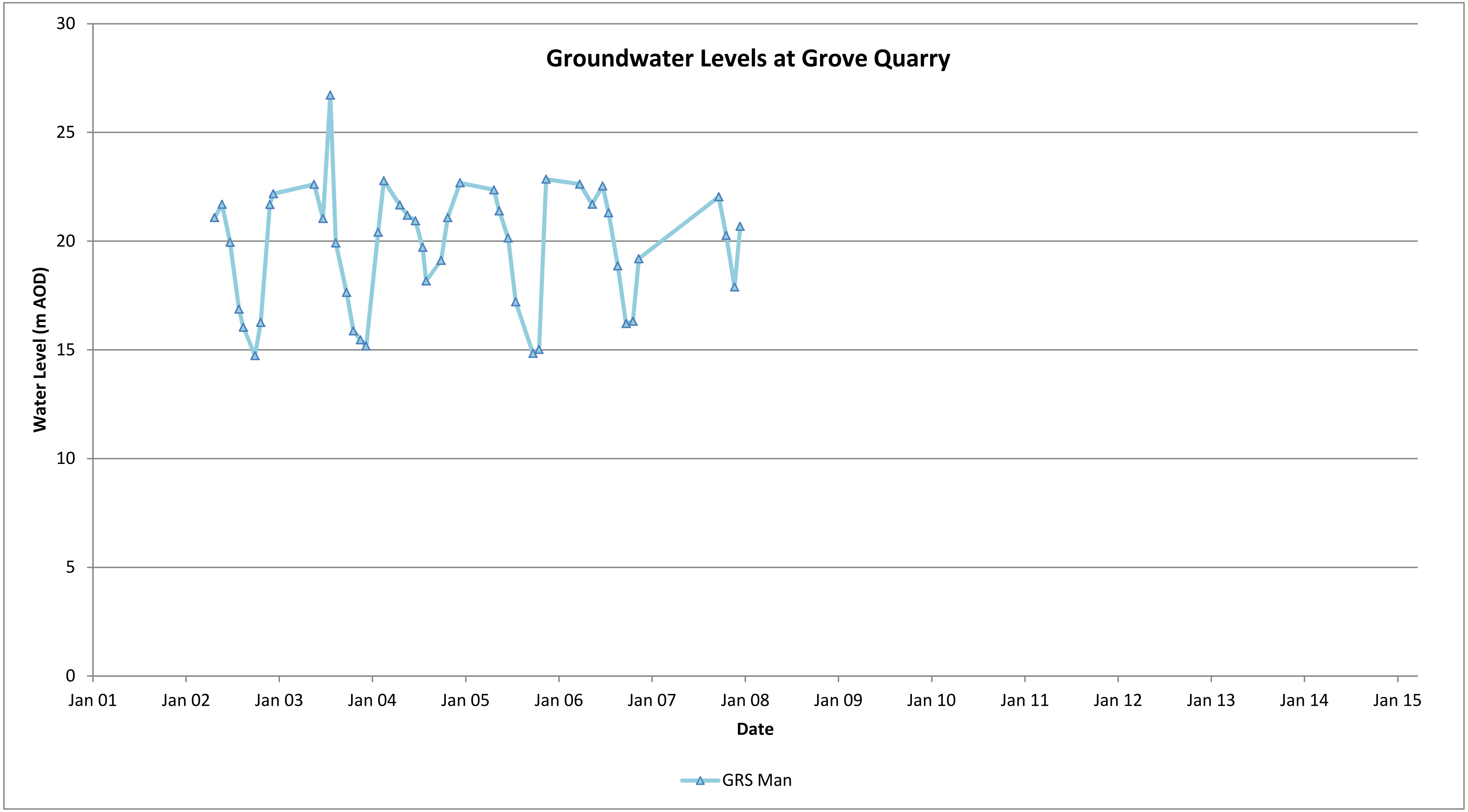


Figure H.8

Groundwater levels at GRS (Grove Quarry)

Date Jun 15	Drawn KHB
Scale dns	Checked BCH
Original A4	Revision 1
File Reference O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.8.xlsx]H8	

Environment Specialists

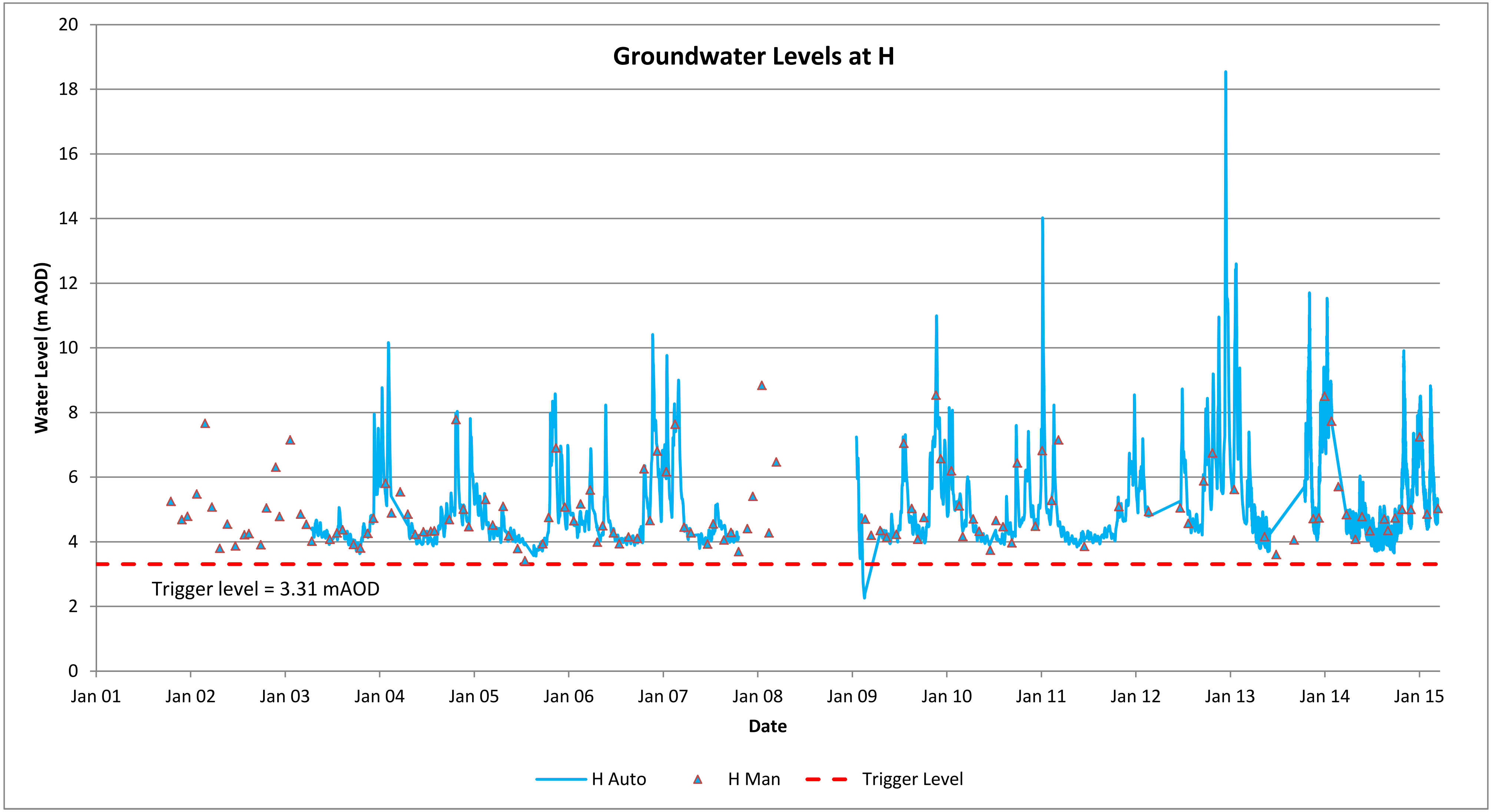


Figure H.9

Groundwater levels at H (Grove Quarry)

Date	Drawn
Jun 15	KHB
Scale	Checked
n/a	BCH
Original	Revision
A4	1

File Reference
O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\Monitoring data\Water level reports\13_June15\[H.9.xlsx]H9

esi Environment Specialists

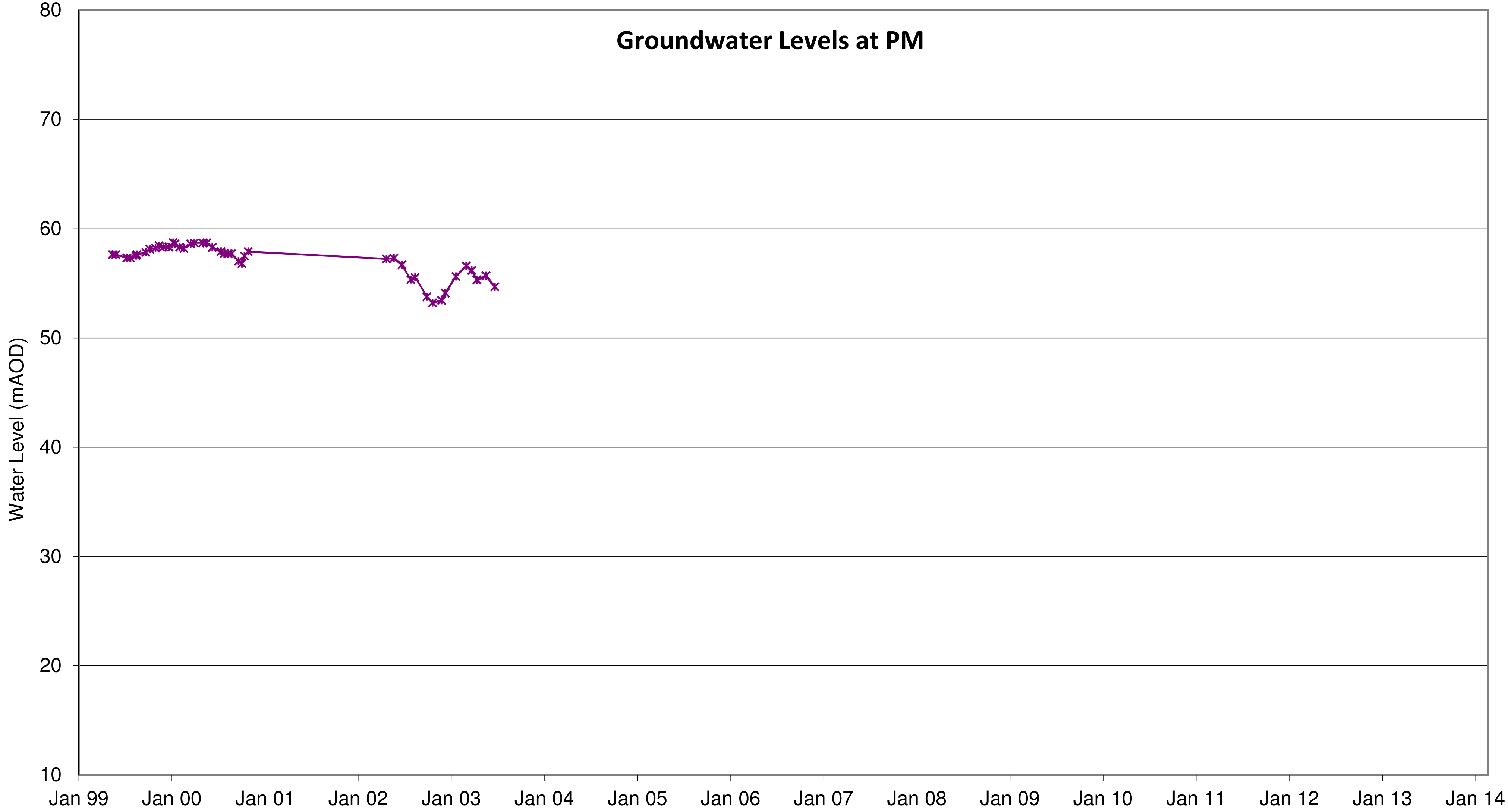


Figure H.10

Groundwater levels at PM (Cornelly Quarry)

Date	Drawn
Apr 14	KHB
Scale: dns	Checked: BCH
Original: A4	Revision: 1

File Reference

O:\6227_Cornelly\data\Raw (incoming) or pre 2013 Data\monitoring\water level reports\12_April14\[H.10.xlsx]H10

Environment Specialists

APPENDIX D

Technical Note on Calculation of Climate Based Assessment Criteria and associated statistical tests

Appendix D1 - Technical Note on Calculation of Climate Based Assessment Criteria and Associated Statistical Tools

Report reference: 6227 WMP Cornelly Quarry, August 2007
Report status: WMP Update August 2007

CONTENTS

FIGURES

APPENDICES

1 INTRODUCTION

1.1 Background

Cornelly Quarry (the "Quarry") is the largest quarry in Wales providing over 1 million tonnes of limestone per year, principally for the steel mill at Port Talbot. It is also an important supplier of aggregates into the local construction industry.

In 1997, applications were made to Bridgend County Borough Council under the Environment Act, 1995 (Review of old mineral permissions – ROMP), for determination of a scheme of conditions in respect of the area of the Quarry covered by those planning permissions (the "ROMP application"). Separate applications were made in respect of the nearby Grove and Gaens' Quarries. The applications were referred to the Secretary of State for Wales in May 1998 (Gaens') and July 1998 (Cornelly and Grove). Due to the commonality of issues at these sites, it was decided that they should be determined as a group. The National Assembly for Wales (now the Welsh Assembly Government) subsequently took on the role of determining authority for the applications.

An Environmental Impact Assessment (EIA) in connection with the ROMP applications for the Quarry was submitted voluntarily in 2004 (WynThomasGordonLewis, 2004). The EIA was based on the continuation and extension of current water management practices at the Quarry. The EIA included a set of proposed planning conditions.

One of the proposed new planning conditions submitted in the EIA was the requirement to develop a Water Management Plan (WMP) for the Quarry (WynThomasGordonLewis, 2004 Appendix 8, C No. 9). The objective of the WMP is to guide the Quarry Operator in its management of water at the Quarry such that any adverse environmental impacts resulting from these activities can be minimised. In order to achieve this, the WMP will:

- Specify the monitoring activities required;
- Outline how the resultant data should be reviewed in order to determine whether the operation of the Quarry has affected any of the monitoring sites;
- Outline the options for management of water at the Quarry and how these could be adjusted in light of any effects detected at any of the monitoring sites.

1.2 Objectives of this Technical Note

For the purposes of the WMP, the Quarry Operator and Regulator need to be able to determine whether any future variations in monitoring data at any of the monitoring sites are due to the effects of climate or are due to other causes (such as land use change, private abstraction and quarry dewatering). There are two components to this technical issue:

1. A mechanism is required that can allow the behaviour of water levels at a monitoring site to be predicted under future climatic conditions (a Climate Based Assessment Criterion);
2. Statistical tools are required that will allow an assessment to be made as to the timing and scale of any Deviation[1] between the water levels predicted by the Climate Based Assessment Criterion and those measured in the future.

1.3 Approach

This technical note presents details of the two tools described above. Section 2 presents a generic description of calculations to be used for generating Climate Based Assessment Criteria. These calculations were originally presented as part of the conceptual model report that underpinned the EIA and were reviewed in detail by the Environment Agency at that time. The calculations have been updated with more recent climate data using several demonstration datasets from the monitoring sites in the area.

[1] In this context, Deviation is defined as the occurrence of a statistically significant difference between the behaviour measured at a site and the behaviour that would be anticipated under 'natural' conditions.

Section 3.1 presents details of statistical techniques that it is proposed should be used to determine whether a Deviation has occurred. This is a two stage process:

1. Firstly standard control chart techniques are applied to identify periods during which there is a sudden or sustained change in the relationship between the observed data and the Climate Based Assessment Criterion.
2. Then statistical tests are applied to confirm whether there has been a statistically significant change in the relationship between the observed data and the Climate Based Assessment Criterion during this period. If a statistically significant change is confirmed, this is considered to be a Deviation.

The use of these techniques is demonstrated in Section 3.2 by artificially adjusting a segment of time series data of a sample data set by a fixed amount to illustrate the sensitivity of the techniques to small changes in water level.

Note that, in this technical note, the techniques are only discussed in terms of water levels. However, they could be equally applicable to flow data.

2 CALCULATION OF CLIMATE BASED ASSESSMENT CRITERIA

2.1 Introduction

This section provides a generic discussion of the calculations that will be used to derive Climate Based Assessment Criterion and the data that they require as inputs. It then illustrates how these calculations can be used to generate a time series of predicted water levels at a site for given antecedent climatic conditions.

The calculations to derive Climate Based Assessment Criteria are based on daily soil moisture balance calculations which use rainfall and potential evapotranspiration data as inputs. The calculations have a number of parameters that affect the way in which the soil moisture balance operates and which control the division of outputs between actual evapotranspiration, runoff and infiltration to groundwater.

The infiltration to groundwater is passed into a '1D store'. This is a simple algebraic device that is used as a 'groundwater model': the rate of outflow in the store is proportional to the level of water in the store. The constant of proportionality of the 1D store is one of the parameters that can be used to adjust the temporal behaviour of both the water levels in the store and the resultant outflows. The water level in the store can be converted to an equivalent measured groundwater level by means of a 'specific yield'.

The values of the parameters used in the calculations presented here were selected partially on the basis of values commonly used for these parameters in regional water resource assessments and partly by 'calibration' against local flow data (e.g. quarry abstraction rates, some stream flow data). These values have not been adjusted since the calculations were originally developed to support the conceptual model in 2003. The match between the simulated and measured water levels at these sites since that time provides a measure of confidence in the calculations and their parameterisation for those sites.

2.2 Data

2.2.1 Rainfall data

The following rainfall data sets are available from the Environment Agency:

Cefn Cribwr (1) – Daily rainfall data for the period Jan 1981 to Jan 02 (with some gaps)

Cefn Cribwr (2) – Daily rainfall data for the period Jan 02 to Dec 05 (with some gaps)

Schwyll - Daily rainfall data for the period Dec 91 to Sept 06 (with some gaps)

Margam - Daily rainfall data for the period Feb 93 to July 06 (with some gaps)

In addition, staff at Kenfig National Nature Reserve monitor rainfall at Kenfig at intermittent (daily/weekly intervals). Data are available for the period Jan 2000 to May 06.

The calculations presented in the conceptual model report (ESI, 2003) were based on the Cefn Cribwr (1) data series. This is an appropriate site for the calculation of the limestone block around the quarry as it is at a similar elevation. As monitoring at this site has been discontinued and there is relatively little overlap with the new monitoring site here, gaps in the data series have primarily been filled by reference to the Schwyll rainfall series. Conversion was by means of the equation Cefn Cribwr (1) = 1.27 x Schwyll (based on the ratio of long term average rainfall at the two sites for periods during which reliable data are available at both sites). Ultimately, it is anticipated that this will be replaced by reference to data from a new rain gauge to be installed at Cornelly Quarry itself.

It is clear from the available data from Kenfig Nature Reserve that rainfall here is lower than at Cefn Cribwr (1) due to the lower elevation of the former. In order to convert the continuous daily time series from Cefn Cribwr (1) to an appropriate series for calculations for the sand dunes, the Cefn Cribwr (1) data have been converted by means of the equation

Kenfig = 0.885 x Cefn Cribwr (1) (based on the ratio of long term average rainfall at the two sites for periods during which reliable data are available at both sites) for the period when there is no data at Kenfig. For the period for which there are rainfall data at Kenfig, the daily rainfall at Schwyll has been factored so that the monthly totals are the same as those measured at Kenfig.

2.2.2 Potential Evapotranspiration data (PE)

Weekly PE data for MORECS square 155 were converted to daily values by distributing the weekly total evenly across each day of the week. There is less spatial variation in PE data and the outputs from the calculations are less sensitive to this parameter and so this has not been varied spatially.

2.3 Soil Moisture Balance Calculations

Recharge to the groundwater system has been calculated using a Penman two store soil moisture balance model implemented in an Excel spreadsheet.

Prior to passing rainfall to the soil moisture store, any runoff is removed. In areas in which the ground surface is relatively impermeable this may be a relatively significant amount (say 10-20%). On areas of permeable aquifer (e.g. limestone or dune sands) runoff is likely to be relatively low although water may effectively bypass the soil zone (see below).

The Penman store model consists of an upper and a lower soil store. The depth of the upper store is the depth up to which roots are able to draw as much water as required. At greater depths of store, water is only available to plants at a reduced rate. A bypass mechanism allowing direct percolation to the unsaturated zone via e.g. macropores or root channels may also be included. Referring to the schematic diagram in Figure 2.1 (a), the Penman store model works in the following manner.

The status of the model is wetting if precipitation is greater than potential evapotranspiration (i.e. *P-PE>0*), otherwise it is drying (*P-PE<0*).

In wetting mode, the direct percolation (i.e. bypass of the soil zone) is a constant percentage of the effective precipitation, i.e. *f (P-PE)*, where *f* is the proportional factor (1). The remaining water *(1-f) (P-PE)* infiltrates the upper soil store (2). When the upper store is full, the excess begins to saturate the lower soil store (3). When the lower soil store is full the excess leaves the lower soil store as percolation to the unsaturated zone (4).

In drying mode, whilst the upper soil store is not dry (5), the soil moisture deficit of the store increases by the shortfall in potential evapotranspiration once precipitation has been taken into account, i.e.

$$\Delta SMD_1 = (PE - P) \quad \text{if} \quad SMD_1 < D_c$$

where

SMD_1 is the soil moisture deficit of the upper store

ΔSMD_1 is the change in the soil moisture deficit of the upper store

D_c is the drying constant.

When the upper soil store is dry, drying of the lower store takes place at a lower rate:

$$\Delta SMD_2 = \gamma (PE - P) \quad \text{if} \quad SMD_1 = D_c$$

where the factor γ represents the drying curve slope

Typical parameter values are as follows *f*=15%, D_c=75 mm, γ=0.3. For the karstic Carboniferous Limestone areas it is likely that the bypass percentage will be higher and a value of 25% has been used.

The output from the soil moisture deficit model (infiltration to groundwater) has then been processed by passing through a two stage store as illustrated on Figure 2.1 (b). The store is characterised by three parameters:

Time constant for lower release

Time constant for upper release

Level for upper release to be activated

The methodology effectively uses catchment averaged rainfall and PE data series to calculate total catchment flow (e.g. in a river). This approach has proved to be very successful in simulating saturated flow in small to medium sized aquifer systems and is used extensively by the Environment Agency in Thames Region (Catchmod).

2.4 Comparison with Data

Whilst the approach described above has been proven to be widely applicable in a variety of settings (including Carboniferous Limestone areas), the effectiveness of the calculations needs to be demonstrated by comparison with field data for the current study area. Comparison of outputs with observed river flows is presented in Appendix D of ESI, 2003. The text below focuses on comparison with observed groundwater levels as this is the primary interest of this technical note.

The status of the 'groundwater store' provides a prediction of groundwater levels in the aquifer. A good match between store volume and groundwater levels indicates that the calculations are effectively simulating the temporal variation in groundwater recharge and discharge from the aquifer system.

2.4.1 Kenfig Dunes

Calculations were developed for the sand dune system at Kenfig using the synthesised daily Kenfig time series (see Section 2.2.1). Key parameters used are:

Sy=0.2 (dune sands)
Store time constant = 180 days
Runoff= 8% (average)
Drying constant (D_c)= 75 mm
Drying curve (γ) = 0.3
Direct percolation (f) = 25%

The results of this calculation are shown in Figure 2.2. Clearly there are a number of simplifications in trying to simulate a complex structure such as the dunes in such a simple manner. However, overall the qualitative fit to the data is reasonable. The summary statistics for the calculations include:

LTA (Feb 93- Jul 06) effective precipitation = 632 mm/a

Percentage of recharge 'overtopping' = 2% (not much 'overtopping' effect in this hydrograph)

The overall range of the simulated and observed groundwater levels during the period of overlap is very close (8.94 to 10.51 mAOD and 8.91 to 10.50 mAOD respectively). There is a slight bias of the calculations to simulate levels lower than those observed (0.1 m on average). However, the current simulation was retained as, on average it was considered to simulate levels better during the critical summer periods. This difference is relatively small compared to the range of levels simulated (7% of range).

2.4.2 Carboniferous Limestone

A similar calculation was set up to simulate recharge processes in the Carboniferous Limestone around Cornelly Quarry. The following parameters were used in the calculations:

Sy=0.005
Runoff=*0%,*
f=25%,
D_c=75 mm,
γ=0.3

Figure 2.3 shows the comparison between the simulated groundwater levels and actual data for borehole 96/11 (just to the east of Cornelly Quarry). There is a good qualitative fit between simulated and observed data. The parameterisation of the calculations has not been modified for the presence of the quarry as it is not clear whether the nature of the workings will increase or decrease the total recharge available (reduced evaporation due to the absence of plants but increased evaporation in areas of open water). The surface of the quarry floors is generally permeable due to the effects of blasting and there does not appear to be significant amounts of runoff.

There is some indication that there has been some drawdown at this site over the period simulated and this is consistent with its position in the immediate vicinity of the quarry.

2.4.3 New Mill Farm Catchment

In this case the groundwater levels in the Triassic marginal facies at the South Cornelly Borehole were simulated. The following parameters were used in the calculations:

Sy=0.015
Runoff=*0%,*
f=25%,
D_c=75 mm,
γ=0.3

The observed and simulated groundwater levels are shown on Figure 2.4. Again, there is a reasonable degree of correlation between the

2.5 Summary

The proposed approach for assessing the effect of climatic variations (principally rainfall rates) on groundwater levels has been shown to be generally successful for the main types of hydrogeological conditions of relevance to the WMP. It is therefore concluded that this approach is appropriate for the purposes required by the WMP.

3 STATISTICAL TOOLS

Control charts are a method commonly used in to monitor processes and produce an early warning whenever a situation deviates from 'normal'. The two main types of control charts used in groundwater monitoring are the Shewart and the Cu-Sum charts. These techniques are used to identify periods during which there is a sudden or sustained change in the relationship between the observed data and the Climate Based Assessment Criteria.

Once such a period has been identified, supplementary statistical tests can be applied to confirm whether there is a statistically significant change in the relationship between the observed data and the Climate Based Assessment Criteria during this period compared to the relationship beforehand (baseline). The choice of tests depends on whether the differences between the observed data and the Climate Based Assessment Criteria are normally distributed or not. The two sample t-test is a well known test that is appropriate for use with populations that are normally distributed with the same variance around their respective means. The Wilcoxen Rank-Sum Test for Two Groups is a non-parametric test that can be used with non-normally distributed datasets.

Section 3.1 presents a brief technical description of the implementation of these methods. This is followed in Section 3.2 by an illustration of the application of these techniques to determine whether there is any deviation between observed water level data and outputs from the calculations presented in Section 2.

3.1 Approach

3.1.1 Shewart Charts

The Shewart control chart is used to detect relatively sudden changes in a process under investigation (e.g. rapid increase/decrease of groundwater level).

Assuming that $x_1, x_2, \dots, x_n$ are n differences between the simulated and measured groundwater levels at the times $t_1, t_2, \dots, t_n$., a Shewart control chart of these differences is obtained by standardising the values of x_i as follows:

$$z_i = \frac{x_i - m}{s}; \qquad i = 1, 2, \dots, n$$

where: m and s are the average and the unbiased standard deviation of the x_i, $i = 1, 2, \dots, n$,

and then plotting them versus the times $t_1, t_2, \dots, t_n$.

In order to identify when the process has deviated from 'normal' the standardised data z_i are compared to a threshold Z (control limit). When the z_i exceed the control limit the process is declared to be 'beyond normal range'. Gibbons suggests that a value of Z of 4.5 should be taken as a level at which a statistically significant change is considered to have occurred.

3.1.2 Cu-Sum Charts

The Cumulative Summation (Cu-Sum) approach not only focuses on the current monitoring value, but also incorporates information from the previous observations. The main advantage of a Cu-Sum over a Shewart chart, is that the Cu-Sum chart is suitable to detect slower, but systematic processes or trends which would not appear as evident by analysing the time series of the raw data or the Shewart chart. This is perhaps more common in the diffuse systems common in hydrogeology.

Assuming that $x_1, x_2, \dots, x_n$ are n differences between the simulated and measured groundwater levels at the times $t_1, t_2, \dots, t_n$.

The Cu-Sum control chart of these differences is obtained by calculating the quantity:

$$S_i = max(0, z_i - k + S_{i-1})$$

Where:

z_i are the standardised differences described in Section 3.1.1;

k is a parameter representing ½ the change that it is appropriate to try and detect (see more discussion on selection of this parameter in Section 3.2);

S_{i-1} is the value of S_i at the previous observation event.

In order to detect a when the process has fallen out of normal range, the values of S_i are compared to a threshold (or control limit) *h*. The selection of the value of *h* should be based on an assessment of the maximum value of S_i that is appropriate – this could be determined by consideration of the typical range of values of S_i during a period in which no Deviation is considered to occur. Note that, the value selected may in part be determined by the frequency of the data (i.e. a larger Cu-Sum will accumulate with daily data if the observed and simulated deviate over a 6 month period than if monthly data is used). If the frequency of monitoring changes then some allowance for this will need to be made (either by sampling the higher frequency data set to a lower frequency or by interpolating between the values in the less frequent data set).

For technical, statistical reasons the value of S_i should not fall below zero. In order to detect trends in the opposite direction, a 'negative' Cu-Sum is calculated. (i.e. the positive Cu-Sum could be used to detect when the observed data falls below the simulated level whilst the 'negative' Cu-Sum could be considered to detect when the observed data rises above that simulated).

The use of the combined Shewart-Cu-Sum control chart gives the advantages of being able to detect sudden changes in the system as well as gradual and consistent shifts, which would not be easily detected by a simple time series plot.

3.1.3 The Wilcoxon Rank-Sum test for Two Groups

The Wilcoxon Rank-Sum Test for Two Groups (Lehmann, 1975) is used to compare a two datasets to check for an increasing/decreasing average value. This is a non-parametric test and, as such, it is robust to outliers and non-detects.

In groundwater monitoring this test is often used to compare a historic dataset with a recent one in order to detect a statistical difference between the two.

To run the Wilcoxon Rank-Sum test the compliance and background data are combined and ranked from 1 to N. The Wilcoxon statistic W is then calculated as:

$$\boldsymbol{W} = \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \boldsymbol{C}_{\boldsymbol{i}} - \frac{1}{2}\boldsymbol{n}(\boldsymbol{n}+1)$$

where:

C_i denotes the ranks of the compliance samples, and

n denotes the number of compliance samples.

In order to determine whether the null hypothesis of no decreased average can be accepted an approximate Z-score for the Wilcoxon Rank-Sum test has to be compared to a critical value of W. The approximate Z-score for the Wilcoxon test is:

$$\boldsymbol{Z} \approx \frac{\boldsymbol{W} - \boldsymbol{E}(\boldsymbol{W}) - 1/2}{\boldsymbol{SD}(\boldsymbol{W})};$$

where:

- *W* is the Wilcoxon statistic as above defined;

- $E(W) = \frac{1}{2}mn$ represents the expected value of *W*;
- *m* is the number of values in the background sample;
- $SD(W) = \sqrt{\frac{1}{12}mn(N+1)\left(1 - \sum_{i=1}^{g}\frac{t_i^3 - t_i}{N^3 - N}\right)}$ is the standard deviation of the *W* statistic adjusted for tied values;
- t_i represents the number of ties in the i^{th} group;
- *g* represents the number of groups of distinct tied observations.

The critical value of *W* is the upper 0.01 percentile of the standard Normal distribution $z_{0.01}$=2.326.

If the Z-score is greater than 2.326, the null hypothesis of no significant difference may be rejected.

An appropriate choice of the background and compliance datasets allows us to use the Wilcoxon Rank-Sum Test for Two Groups as a means to identify a statistical evidence of decreasing average.

3.1.4 The two sample t-test

The t-test is the most widely used method for comparing two independent groups of data, however it presents some problems when applied to non normal datasets.

The null hypothesis of the test is that the difference between the averages of the two datasets equals a number δ_0. The test statistics is:

$$t_0 = \frac{(\overline{X} - \overline{Y}) * \delta_0}{s_p\sqrt{\frac{1}{m} + \frac{1}{n}}} \qquad (1)$$

where:

$\overline{X}$ is the average of the data over the period during which a change appears to have occurred;

$\overline{Y}$ is the average of all the rest of the data;

$s_p = \sqrt{\frac{(m-1)*s_x^2 + (n-1)*s_y^2}{m+n-2}}$ is the pooled standard deviation estimate;

s_x and s_y the sample variances of the two populations;

<u>*m*</u> and *n* the sample sizes of the x and y datasets respectively

In the case that the test statistics is greater than the critical value $t_{m+n-2,1-\alpha}$ (which should be looked up in the test statistical tables), the null hypothesis should be rejected.

3.2 Application

3.2.1 Existing data sets

The application of these techniques is illustrated by reference to the observed and simulated data for the Kenfig Dunes sites as discussed in Section 2.4.1.

First the existing sequence of observed and simulated data were taken to form a ‘baseline’ for the statistical techniques. This created a series of pairs of observed:simulated data values at approximately monthly intervals for the period Jan 1997 to May 2006. Figure 3.1 shows the combined Cu-Sum and Shewart chart for the differences between the observed and simulated data (lower plot). The actual observed and simulated data are shown in the upper plot for comparison.

The Shewart chart shows that the control limit is not exceeded at any point in the historical time sequence.

The ‘positive’ Cu-Sum chart, conversely, shows that in the early part of the time series (1997 drought) there are some small but consistently positive differences between the simulated and observed data, whereas the ‘negative’ Cu-Sum chart shows a similar consistency in negative differences in the following part of the time series (through to the heavy rainfall in 2000). Following this there is relatively little consistent difference between simulated and observed data for the remaining time period. These differences can be seen in the observed and simulated data can be seen in the upper plot. It is not clear whether these differences are due to limitations of the calculations or inaccuracies in the input rainfall time series during this period.

The maximum (minimum) value represented in the positive (negative) Cu-Sum chart is less than +20 (greater than -26 respectively). If the calculations can be qualitatively accepted as an appropriate simulation of the groundwater conditions at this site (see discussion in Section 2.4.1) and it is considered that there is no general background trend in the differences during this period then, given that the period includes some fairly extreme climatic conditions (drought and flood), this range of Cu-Sum values can be considered to be appropriate levels at which to detect that a significant change has occurred. If the calculations could be improved to provide a more consistently good fit between observed and simulated levels, then the critical values of Cu-Sum can also be reduced.

3.2.2 Application to ‘future’ scenario with applied drawdown

In order to assess how effective the technique is at detecting the presence of a small but consistent drawdown in groundwater levels, a sequence of three years was added to the end of the time series and then manipulated to introduce a consistent difference between observed and simulated levels.

The data pairs for 2002 (which was considered to be a ‘typical year’) were repeated three times to create the ‘future’ sequence. This ‘future’ sequence was then modified by reducing the observed groundwater levels by a constant value (i.e. equivalent to a non-climate related drawdown occurring in the data). The Cu-Sum and Shewart charts were then calculated to see what size of deviation between the measured data and the simulated groundwater levels could be detected.

The results of this exercise are shown in Figures 3.2, 3.3 and 3.4 for drawdowns of 0.1, 0.2 and 0.3 m respectively. K was set at 0.05 m for this exercise, but in general will be set to half the difference that needs to be detected – for instance the Significance Criteria. The sensitivity of these results to K is shown in Figure 3.5.

From inspection of these figures, it can be seen that the Shewart approach does not detect these small but consistent changes (a change of around 0.6 m would be required to breach the Shewart control limit). The change of 0.1m would be confirmed in around 28 months (although the upward trend would have been apparent for the whole of this period), the change of 0.2 m would be confirmed in 9 months).

Comparison of the observed and simulated hydrographs in the upper plots shows that it is unlikely that a change of 0.1 m would be detected by visual comparison alone and that even a change of 0.2 m would be hard to be confident about.

A number of points are apparent from this exercise:

- The Cu-Sum approach is more sensitive and objective than visual inspection of the hydrographs.
- The length of time that the Cu-Sum takes to detect a change is inversely related to the size of the change (i.e. bigger changes are detected more quickly).
- The length of time that the Cu-Sum takes to detect a change is also related to the quality of the calculations (changes will be detected more quickly with a better match between observed and simulated data).
- The Shewart Chart is less sensitive than the Cu-Sum approach in detecting small but consistent changes. However, it would be effective at detecting a larger but more abrupt change.

3.2.3 Statistical Confirmation

The Cu-Sum chart method is dependent on time correlation effects and so, where water level changes are very gradual in comparison to the frequency of monitoring, this methodology may falsely indicate a systematic change in water levels. Once the Cu-Sum chart detects an apparent systematic change, it is therefore important to double check that a statistically significant difference is present in the data.

To achieve this, the two sample t-test or the Wilcoxon test can be used to compare the model residuals during the ‘baseline’ and apparently affected periods. In this case, the Wilcoxon test was used to confirm that there was a statistically significant change between the last three years of data (i.e. the period over which a change in the data was artificially applied) and the rest of the dataset. The Wilcoxon test was used as the model residuals were not normally distributed.

3.3 Summary

The example presented above suggests that the combined Shewart-Cu-Sum approach should be effective at detecting both abrupt changes in observed and simulated water levels and small but consistent changes. The sensitivity of these techniques in detecting changes in water level is primarily controlled by the quality of the fit between the observed and simulated data over a representative ‘baseline’ period. Where a good fit cannot be achieved, simpler approaches may be appropriate.

Once a period of apparent variation between the Climate Based Assessment Criterion and the observed data has been identified, it is important to carry out supplementary statistical tests to confirm this conclusion. To achieve this, the two sample t-test or the Wilcoxon test can be used.

In all cases, conditions at adjacent sites should be considered wherever possible in order to confirm the conclusions of techniques such as these.

4 REFERENCES

ESI, 2003. Cornelly Group of Quarries: Conceptual model of the local hydrogeology

R. Gibbons "Statistical Methods for Groundwater Monitoring" John Wiley & Sons, Inc

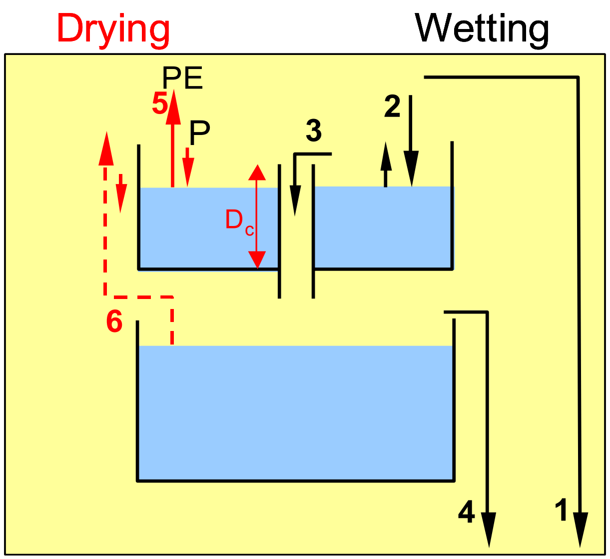
Lehmann, E.L. (1975) Nonparametrics: Statistical Methods Based on Ranks. San Francisco: Holden-Day, Inc.

WynThomasGordonLewis, 2004. Environment Act 1995: Review of Mineral Planning Permissions Cornelly Quarry Environmental Impact Assessment

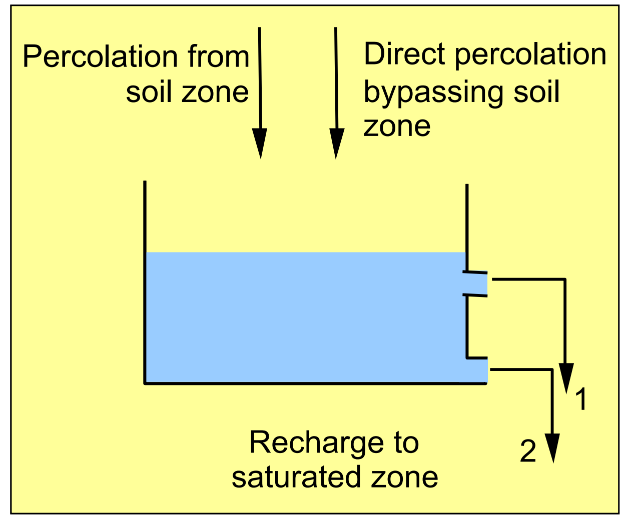
Appendix D.1 Parameters for Climate Based Assessment Criteria at Each Site

To be completed after first annual review after formal adoption of WMP.

(a)



(b)



(b) ‘Two Stage’ Linear Store Model

Outflow rate is proportional to volume in store

Recharge to saturated zone comprises

1. Outflow once volume (saturation) has reached critical level

2. Slower release also dependent on volume in store

Figure 2.1

(a) PENMAN TWO STORE SOIL MOISTURE BALANCE MODEL

(b) LINEAR CATCHMENT STORE MODEL FOR UNSATURATED ZONE

Date: Dec 06	Drawn: MJS
Scale: nts	Chk'd: MJS
Original: A4	Rev: 1
File Reference: O:\6227_Cornelly\calcs\WMP supporting calcs\recharge\SMB	

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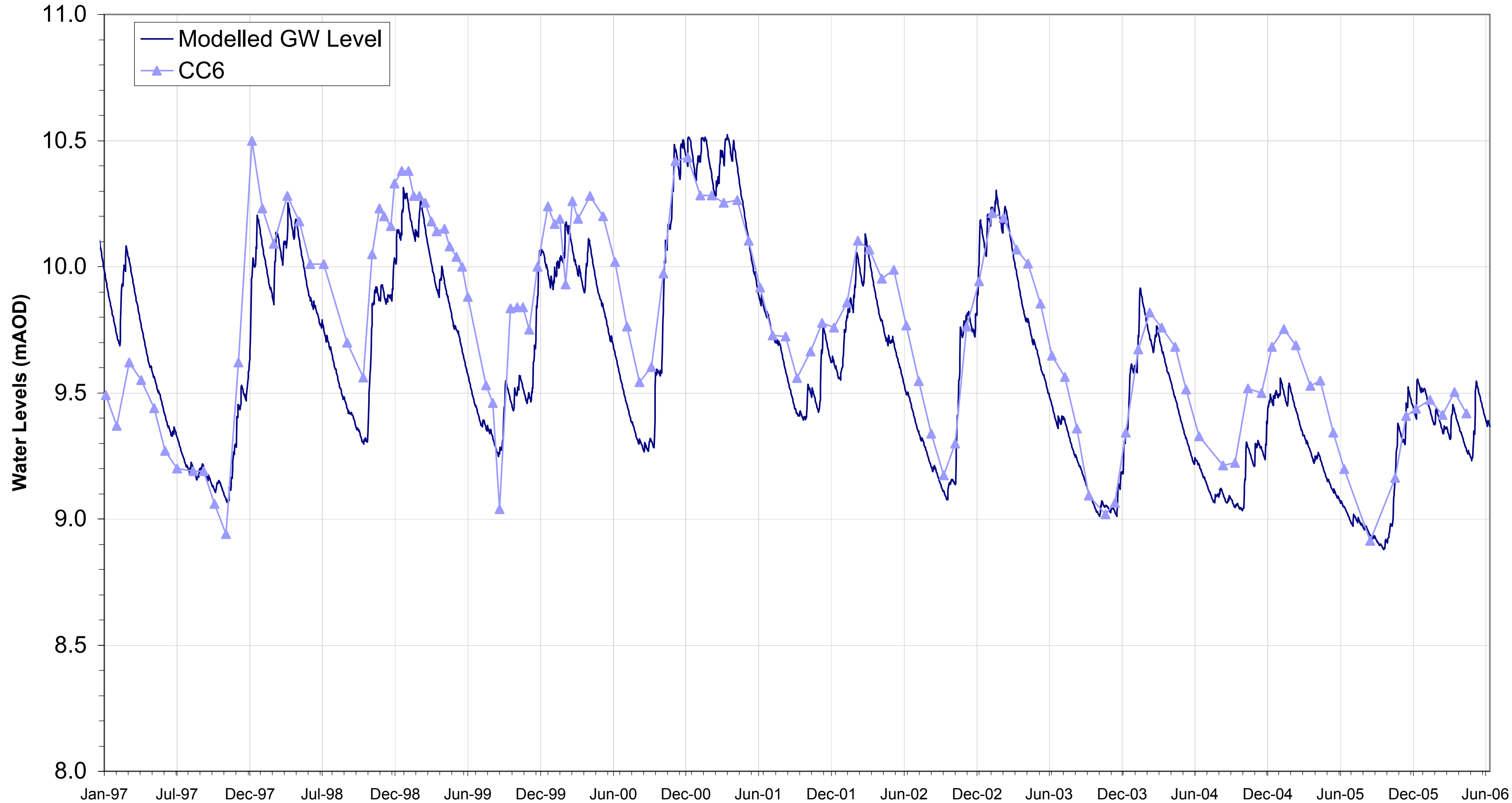

Figure 2.2

Modelled and Actual Groundwater Levels - Kenfig Dunes

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Scale: **nts**	Chk'd: **MJS**
Original: **A4**	Rev: **1**
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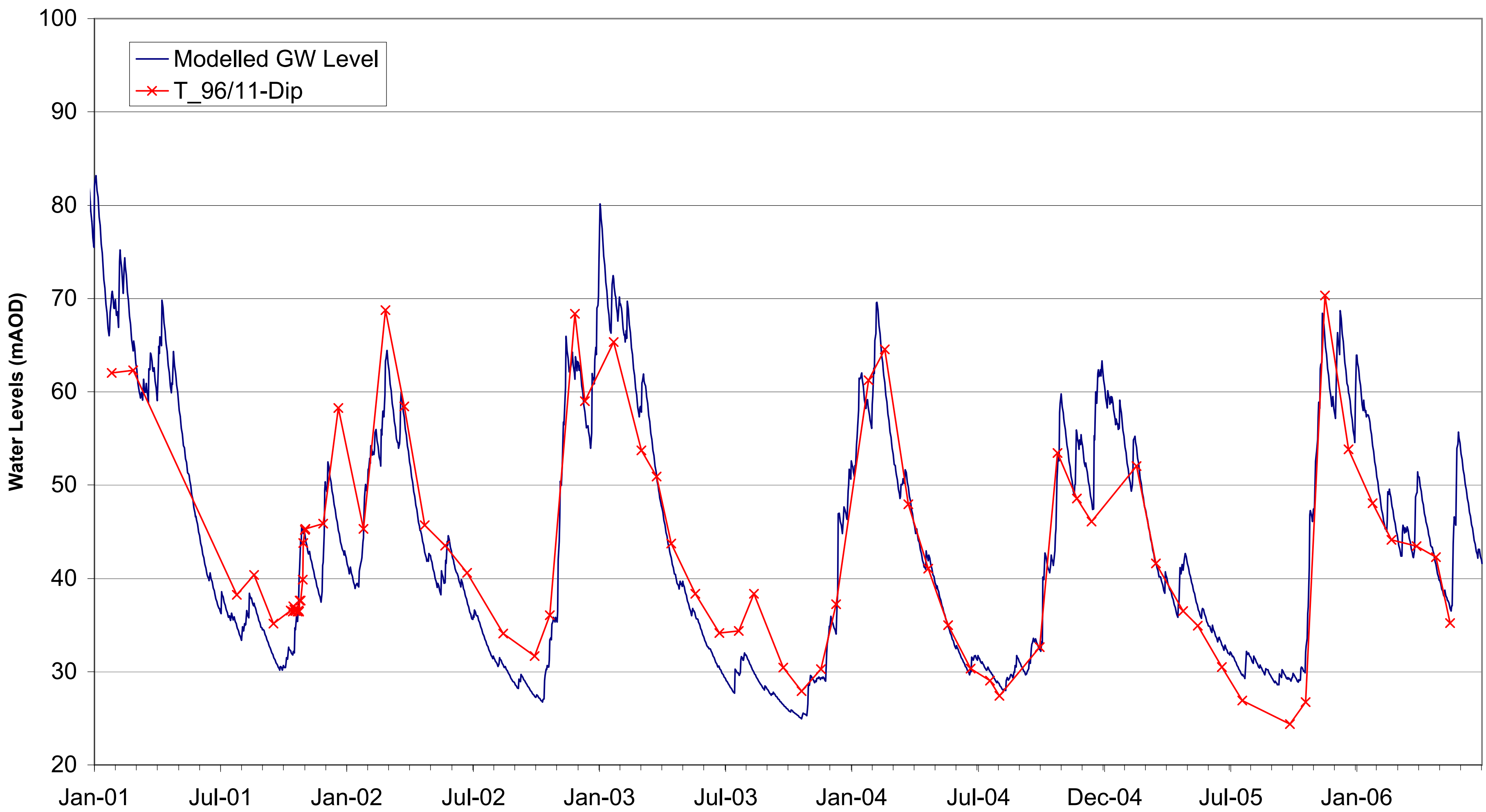

Figure 2.3

Simulated and observed groundwater levels in the Carboniferous Limestone

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Dec 06	MJS
Scale: nts	Chk'd: MJS
Original: A4	Rev: 1

File Reference: O:\6227_Cornelly\calcs\WMP supporting calcs\recharge\Carb Lst Recharge.xls

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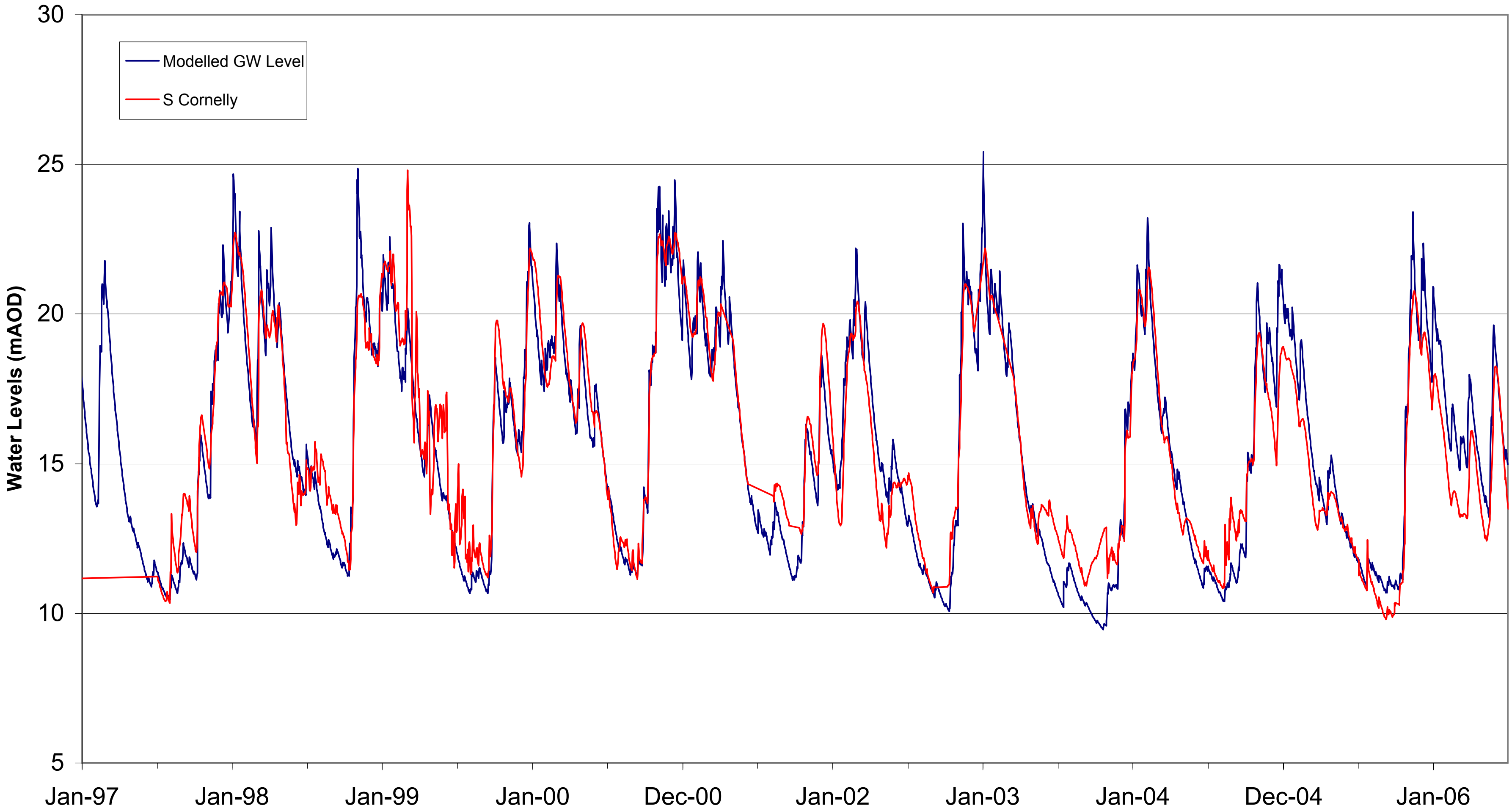

Figure 2.4

Simulated and observed groundwater levels in the Triassic

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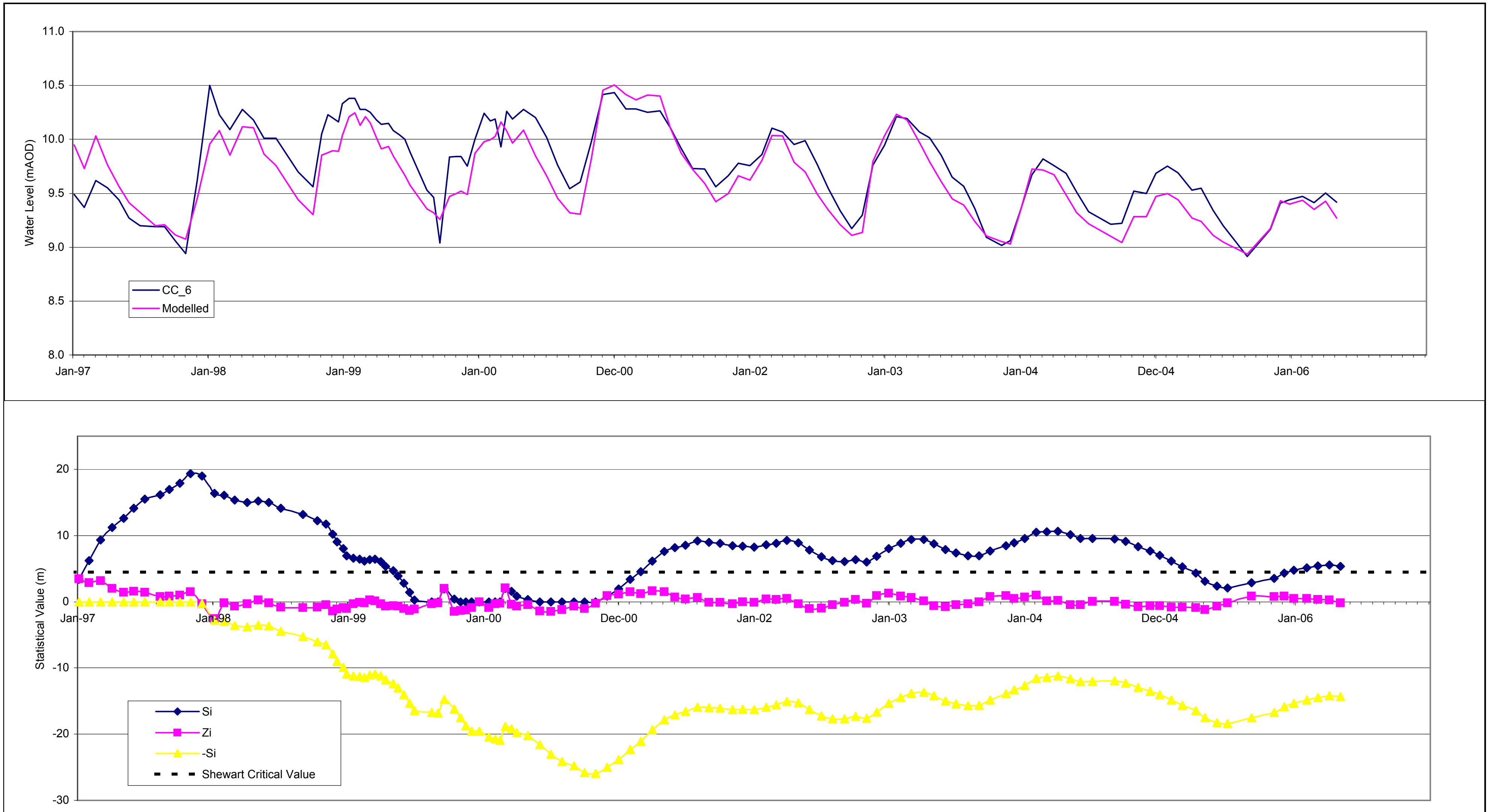

Figure 3.1

Measured and simulated time series data and resultant Shewart and Cusum charts

Historical data only

K = 0.05

Date: Dec 06	Drawn: MJS
Scale: nts	Chk'd: MJS
Original: A4	Rev: 1
File Reference: 6227\calcs\WMP Calcs\stats\Cu-Sum and Shewart charts.xls	

esi soil & groundwater

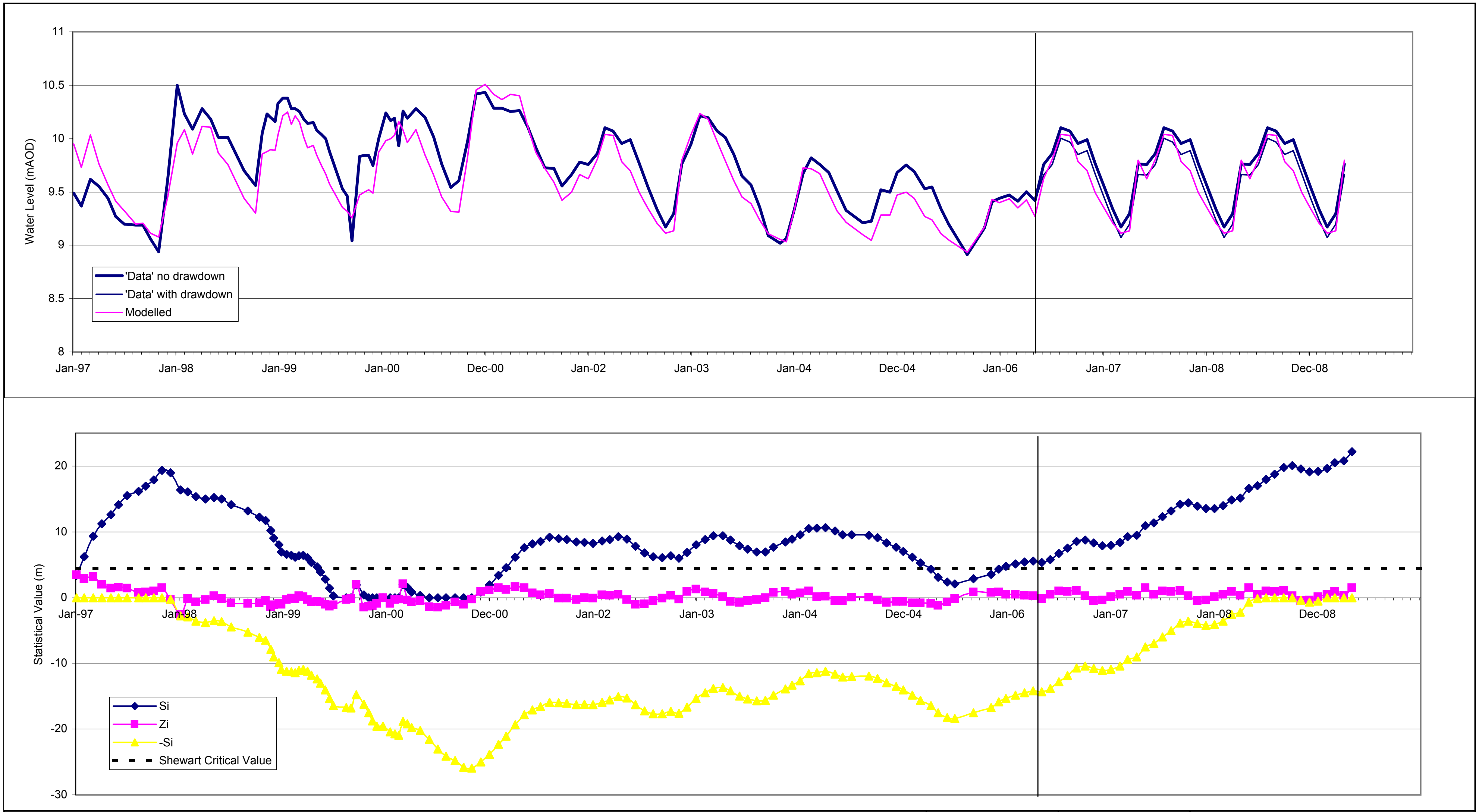

Figure 3.2

Measured and simulated time series data and resultant Shewart and Cusum charts

Includes a 3 year repeated cycle beyond May 2006 K = 0.05 Drawdown = 0.1 m

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Scale: nts	Chk'd: MJS
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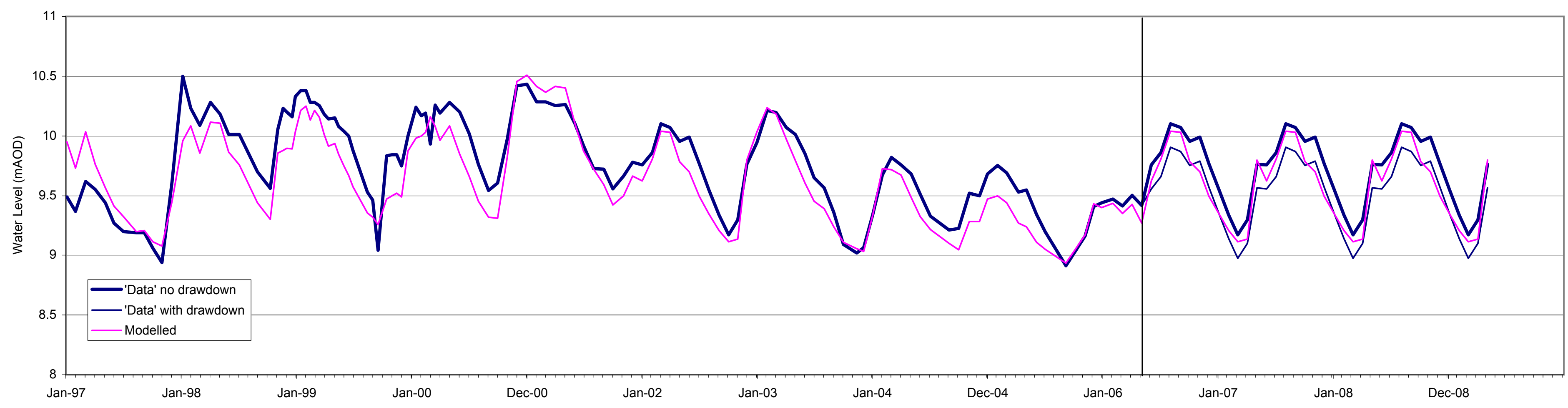

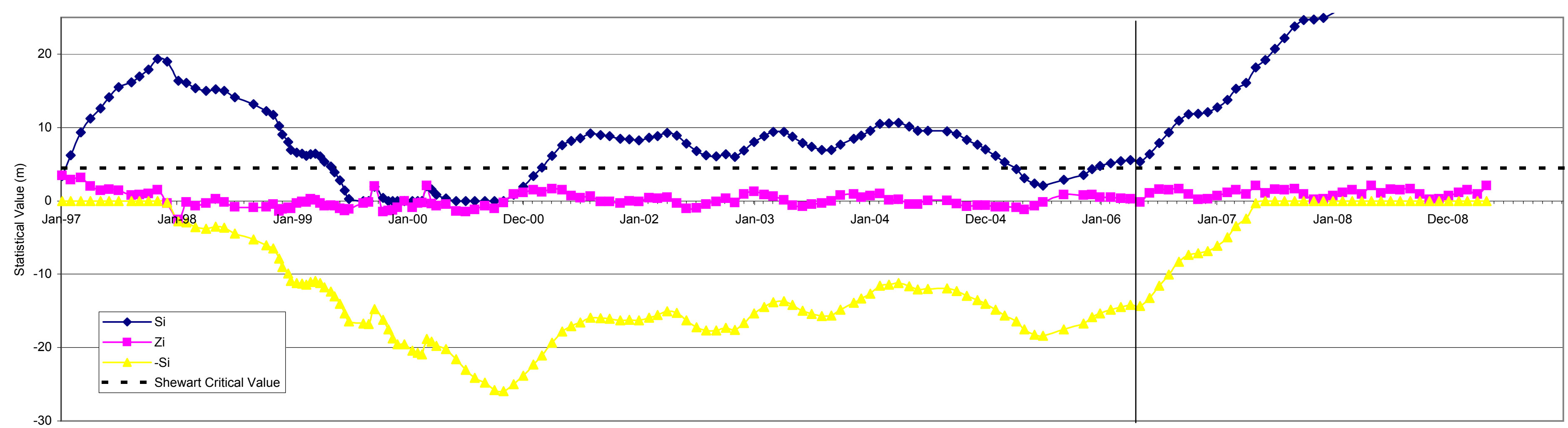

Figure 3.3

Measured and simulated time series data and resultant Shewart and Cusum charts

Includes a 3 year repeated cycle beyond May 2006 K = 0.05 Drawdown = 0.2 m

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Scale: nts	Chk'd: MJS
Original: A4	Rev: 1

File Reference: 6227\calcs\WMP Calcs\stats\Cu-Sum and Shewart charts.xls

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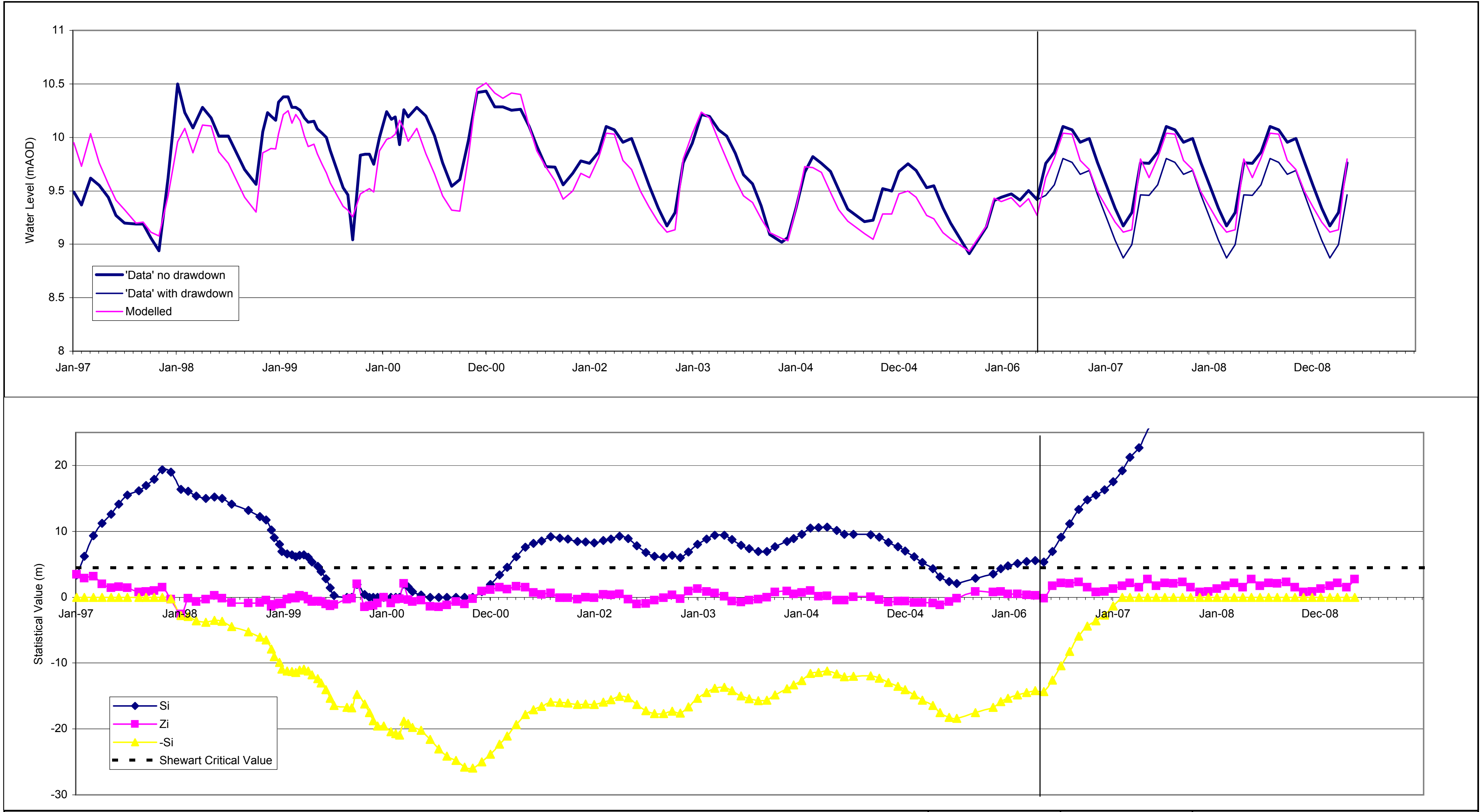

Figure 3.4

Measured and simulated time series data and resultant Shewart and Cusum charts

Includes a 3 year repeated cycle beyond May 2006 K = 0.05 Drawdown = 0.3 m

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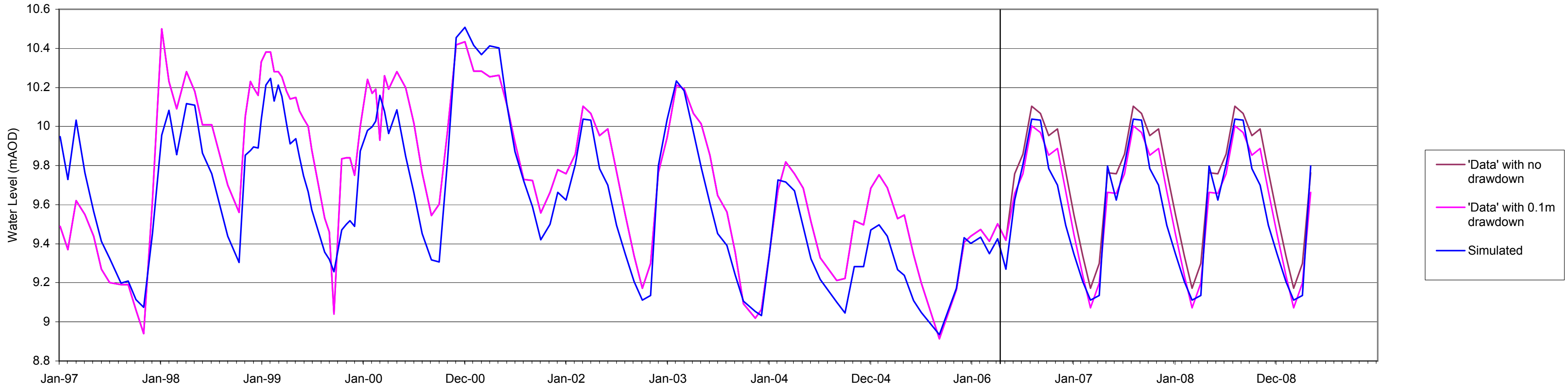
Scale: nts	Chk'd: MJS
Original: A4	Rev: 1

File Reference: 6227\calcs\WMP Calcs\stats\Cu-Sum and Shewart charts.xls

esi soil & groundwater



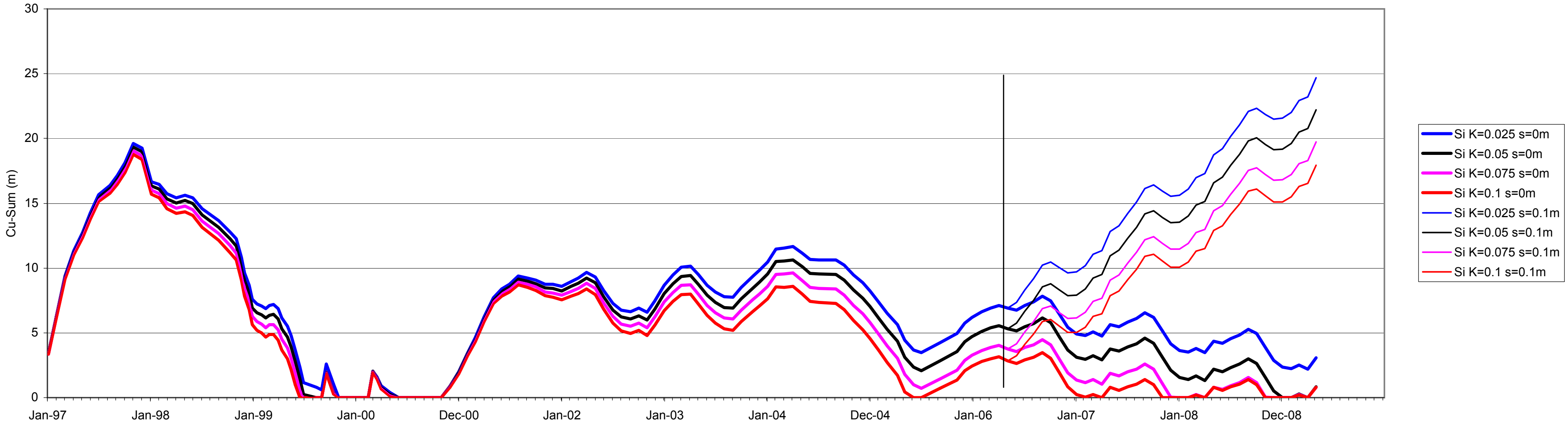


Figure 3.5

Sensitivity of Cusum results to value of K

Date: Dec 06	Drawn: MJS
Scale: nts	Chk'd: MJS
Original: A4	Rev: 1
File Reference: 6227\calcs\WMP Calcs\stats\Sensitivity analysis.xls	

soil & groundwater

Appendix D2 – Technical Note on the conceptual model and method used in Climate Based Assessment Criteria

Prepared for Lafarge Tarmac Ltd

Report reference: 6227 WMP Cornelly Quarry, July 2015

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1 INTRODUCTION

1.1 Background

Cornelly Quarry (the “Quarry”) is the largest quarry in Wales, providing over 1 million tonnes of limestone per year, principally for the steel mill at Port Talbot. It is also an important supplier of aggregates into the local construction industry.

Cornelly Quarry is currently the subject of an Environment Act ‘ROMP Review’ which will update the planning conditions controlling future operations at the Quarry. The Applicant, Lafarge Tarmac Ltd, has proposed a series of updated planning conditions as required by the Review, including a commitment to carry out the development in accordance with a ‘Water Management Plan’ (WMP).

The WMP is intended to guide the Quarry Operator in its management of water at the Quarry such that any adverse environmental impacts resulting from these activities may be prevented and/or reversed. As such the WMP will specify the following;

- details of water management
- monitoring requirements and activities required
- outline the process for review and reporting of collected data
- provide guidance on the mechanism for determining whether a significant deviation has occurred and identifying resulting actions
- outline available planned mitigation measures and instructions on their implementation

1.2 Objectives and Approach

The WMP requires the Quarry Operator and Regulator to determine whether any future variations in the data collected from any of the monitoring sites are due to the effects of water management at the quarry. As most of the monitored parameters (principally water levels and flows) are strongly affected by antecedent rainfall, it is necessary to assess what effect rainfall would have had on these data so that Deviation[1] from expected conditions can be identified. For the Cornelly WMP this is achieved by means of Climate Based Assessment Criteria. The background to the approach used is set out in detail in Appendix D1 of the WMP. This technical note describes the implementation of the Climate Based Assessment Criteria for the Cornelly WMP.

Section 2.1 discusses the conceptual model used in the transient water balance calculations that generate the Climate Based Assessment Criteria and is followed in Section 2.3 by a description of the process used to estimate ‘natural water level/flow’ conditions. Section 3.3 presents three case studies which demonstrate the correct use of the statistical tools to highlight any trends in measured groundwater level.

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[1] In this context, Deviation is defined as the occurrence of a statistically significant difference between the behaviour measured at a site and the behaviour that would be anticipated under ‘natural’ conditions.

2 CLIMATE BASED ASSESSMENT CRITERIA

2.1 Conceptual Model

A schematic diagram of the conceptual model used to generate the Climate Based Assessment Criteria is shown in Figure 2.1.

The method to derive the modelled groundwater levels used in Climate Based Assessment Criteria is based on a Penman soil moisture balance model and a subsequent system of 1-D 'stores'.

The parameters which affect the way the soil moisture balance operates and which control the division of outputs between actual evapotranspiration, runoff and infiltration to groundwater are presented in detail in Appendix D1.

Infiltration to groundwater from the unsaturated zone (soil moisture balance) is passed into one of two stores; slow (matrix) store and fast (fracture) store. Together these form a simple 'groundwater model' as described in Section 2.3. Modelled groundwater levels are derived by converting the sum of the stores into an equivalent measured groundwater level using a specific yield.

2.2 Model Parameters

The model stores parameters defined in Table 2.1 below and displayed on the control page of each CBAC sheet are used to calculate the volume of water in each store and resultant discharge volume.

Table 2.1 User-defined parameters used to calculate modelled groundwater levels

<table>
<tr><th>Parameter</th><th>Units</th><th>Description</th></tr>
<tr><td>Direct percolation</td><td>%</td><td>The percentage of recharge which bypasses the soil moisture balance calculations and flows directly to groundwater, entering the fast store.</td></tr>
<tr><td>Slow store starting volume</td><td rowspan="2">mm</td><td rowspan="2">The model calculates the daily change in volume in groundwater stores and tracks the dischargeable volume of groundwater held in stores.
This parameter is used to set a starting volume in each store. Because the store calculations are based on a unit area, volumes are expressed in mm; they are multiplied by the catchment area and divided by 1000 to derive a true volume of water (m^3).
Due to the long period between the model beginning and calibration to measured water levels this parameter is not important in this case and values are set to 0 mm for all models.</td></tr>
<tr><td>Fast store starting volume</td></tr>
<tr><td>% Slow</td><td>%</td><td>The percentage of drainage water from the soil zone which infiltrates to the slow store (all remaining drainage water enters the fast store).</td></tr>
<tr><td>T Slow</td><td rowspan="2">Days</td><td rowspan="2">Used in calculating the volume of water discharged from the Slow/Fast stores. Each day, the rate of discharge (m^3/d) from a store is given by V/T where V is the volume within the store (m^3) and T is measured in days.</td></tr>
<tr><td>T Fast</td></tr>
</table>

Parameter	Units	Description
Slow store max	mm	The depth of water in the slow store at which overtopping occurs.
Specific yield	dimensionless	Used to convert the sum of the store levels into a groundwater level. Separate values are assigned to the matrix and fracture stores.
Starting head	mAOD	The starting value for modelled groundwater

2.3 Stores Processes

Descriptions of the processes which occur within the groundwater model are presented below, in accordance with Figure 2.1. A detailed description of the soil moisture balance calculations is presented in Appendix D1.

2.3.1 Inflow

Water leaving the soil zone and entering the saturated zone originates from two processes:

1. Direct percolation (recharge bypassing the soil zone). This is calculated as a user-defined proportion of the excess rainfall (rainfall-runoff-potential evaporation).
2. Drainage from the soil zone (calculated by the soil moisture balance).

Slow store: the slow store receives a user-defined percentage (*% slow*) of the drainage from the soil zone.

Fast store: The fast store receives the bypass recharge. Additionally, the remaining proportion of water draining from the soil zone enters the fast store.

2.3.2 Outflow

The volume of water discharged from each store is calculated as the volume in the store divided by a user defined value (*T_fast* or *T_slow*).

An overtopping facility within the slow store enables all water above a user-defined level (*slow store max*) to be directly discharged.

The model allows for calculation of runoff, which is removed prior to entering the soil moisture balance and added to discharge from the stores to make up total daily discharge (m^3/d). However, for the Cornelly Quarry calculations, runoff is predicted to be very little as water is expected to infiltrate into the permeable aquifers (e.g. limestone or dune sands), therefore no runoff is included.

It is this total daily discharge which is used to calibrate both the Burrows Well and Cornelly Quarry Pumping flow CBACs.

2.3.3 Modelled groundwater level

Following the removal of discharge from the stores, the levels are converted to mAOD using a user-defined starting head;

$$Modelled\ groundwater\ level\ (mAOD) = Starting\ head\ (mAOD) + \frac{Fast\ store\ (mm)}{(Sy\ fracture\ x\ 1000)} + \frac{Slow\ store\ (mm)}{(Sy\ matrix * 1000)}$$

This modelled groundwater level is used in the groundwater level CBACs to calibrate to a measured groundwater level time series.

3 APPLICATION OF METHODOLOGY

3.1 Model Calibration

Each transient water balance model was calibrated manually, taking into consideration the standard deviation and mean error statistics. The resultant calibration models (with all the associated parameters) are appended to this document.

In general there was a good degree of commonality in the parameters used and, where these had a physical basis (e.g. specific yield) the results used were consistent with the local conceptual understanding of the aquifers.

3.2 Use of Statistics

The difference between observed and modelled water levels/flows is assessed statistically using the Shewart and Cusum approaches as discussed in Appendix D1. The two key statistics used are:

> z_i – the standardised error (difference between observed and modelled water levels/flows normalised for mean error and standard deviation) and
>
> *CuSum* – a statistic that accumulates sequential values of z_i to highlight periods during which model and observed consistently differ in one direction.

In order to accurately and rapidly observe any future trends deviations between observed and modelled water levels/flows, an appropriate baseline dataset must first be defined. The quality of model fit in the baseline period can be assessed through the mean error and standard deviation error. Should these statistics incorporate groundwater trends or poorly fitted data (non-baseline data), the errors will be larger and subsequently the standardised error (Zi) will be less sensitive to minor changes in groundwater level. This will also lead to large trends in CuSum during the baseline period.

In general the baseline period has been set to the end of the current period of data availability as discussion between staff from Natural Resources wales and ESI (on behalf of Lafarge Tarmac) had concluded that only a few sites showed any potentially significant deviation between observed and simulated data to date. The exceptions are discussed below.

The WMP sets out that a Deviation has occurred when either: z_i exceed 4.5 or the CuSum exceed a specific value (set individually for each site and generally based on the largest value of CuSum observed in the baseline period). The Deviation should be confirmed by carrying out further statistical tests of the data before and after the occurrence of the apparent Deviation to confirm that they are statistically different (as described in Appendix D).

3.3 Case Studies

The following case studies are presented to demonstrate the application of the methodology and to highlight the importance of a carefully chosen baseline in identifying trends in groundwater levels using cu-sum statistics.

3.3.1 Location E calibration

Observed groundwater levels at OBH E show a decline of 6.8 m compared to modelled groundwater levels over the 13 year period of available data. This decline seems to start shortly after the end of the period when water was being discharged to the nearby Pant Mawr quarry (end 2002) although, as monitoring at E only started in 2002, it is not entirely clear that what the trends were before this point.

Figure 3.1 shows the CBAC model for OBH E calibrated to fit the early data using a visual calibration. In this case, the calculation of the statistics includes all available time series data. The resultant CuSum plot does not begin to highlight any immediate decline in groundwater levels: initially the CuSum rises (z_i is generally negative) and then only falls later. This is because it is calculating an average error for the whole period and so, in the early stages, the error (modelled minus observed) is negative.

The baseline dataset for this location has therefore been re-defined for a reduced period: from the beginning of the time series until July 2004 when the decline in levels starts to become apparent. Figure 3.2 now clearly identifies the start of the period of decline in groundwater values following the end of the baseline dataset.

In future, given that water levels now appear to have largely stabilised again, the baseline period could be re-defined to the more recent period (and the model re-calibrated to this) so that the CBAC could be used to detect any further changes.

3.3.2 South Cornelly

Similarly to location E, when all available data is included in the calculation of mean error and standard deviation error statistics, the plot of CuSum statistics at South Cornelly is potentially misleading. Figure 3.3 shows the South Cornelly CBAC model where statistics (mean error and standard deviation) are calculated using all available time series data. The CuSum plot suggests that a long-term declining groundwater level trend is occurring; however visual observation of the plot of measured and modelled data does not confirm this.

Figure 3.4 highlights that the use of baseline data for a shorter period (September 2002 – March 2015) to calculate mean and standard deviation errors and removal of the poorly-fitted data (1995 – 2001) from the CuSum statistics produces a more accurate picture of trends in groundwater levels.

This implies that generally there were no potentially significant changes in water levels at the site until 2012/13 when observed water levels started to be above modelled levels (by an average of 0.8 m). There are some inadequacies in the pumping rate data for the site over this period but there does appear to have been an increase in the discharge to Grove Quarry. This would therefore demonstrate the potential effectiveness of this Planned Mitigation Measure in raising water levels as required.

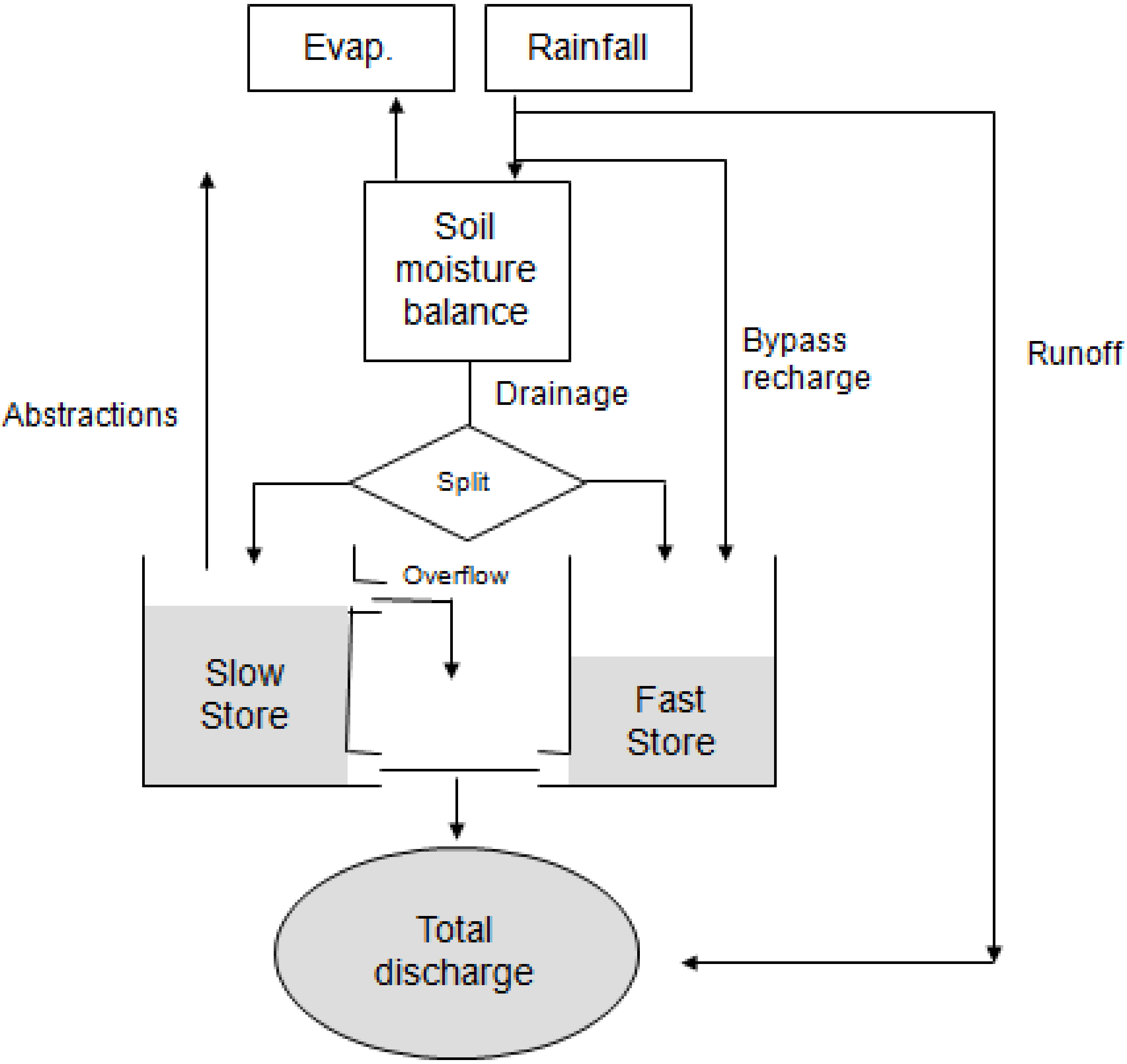


Figure 2.1
Climate Based Assessment Criteria conceptual model flow diagram

Date July 2015	Drawn KHB
Scale A4	Checked JRR
Original A4	Revision 1
File Reference O:\6227\Reports\New Draft WMP\Appendices\Figure2.1.doc	

esi Environment Specialists

Runoff Calculation Parameters (Location E)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	5	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.007	18.5
GW	1,420,082	0.007 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	70	%
T Slow	50	days
T Fast	50	days
Slow store max	100	mm

Stats

Baseline dataset for calculation of statistics:
n/a

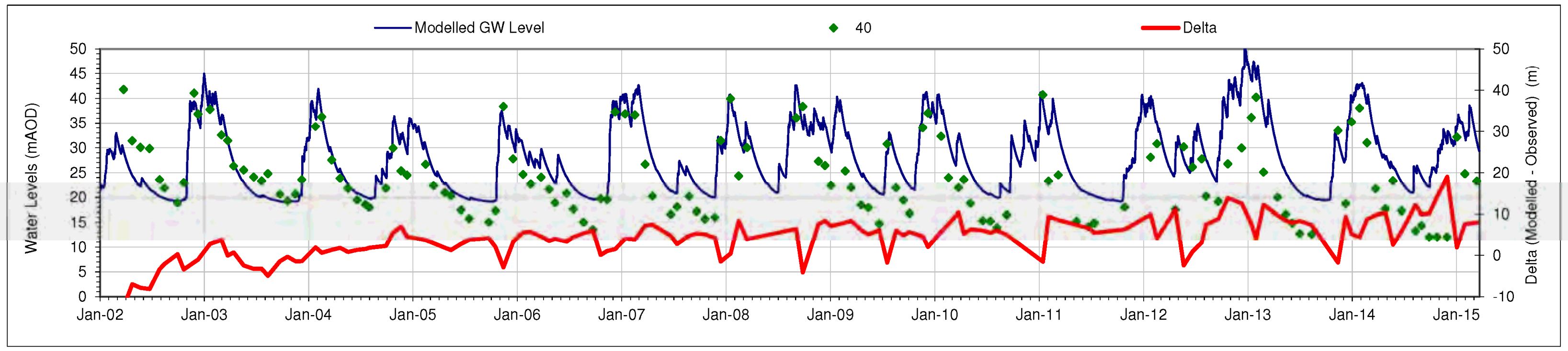
K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	4.03	m
ST Dev Error	4.77	m
Dummy value for Z_i	0	

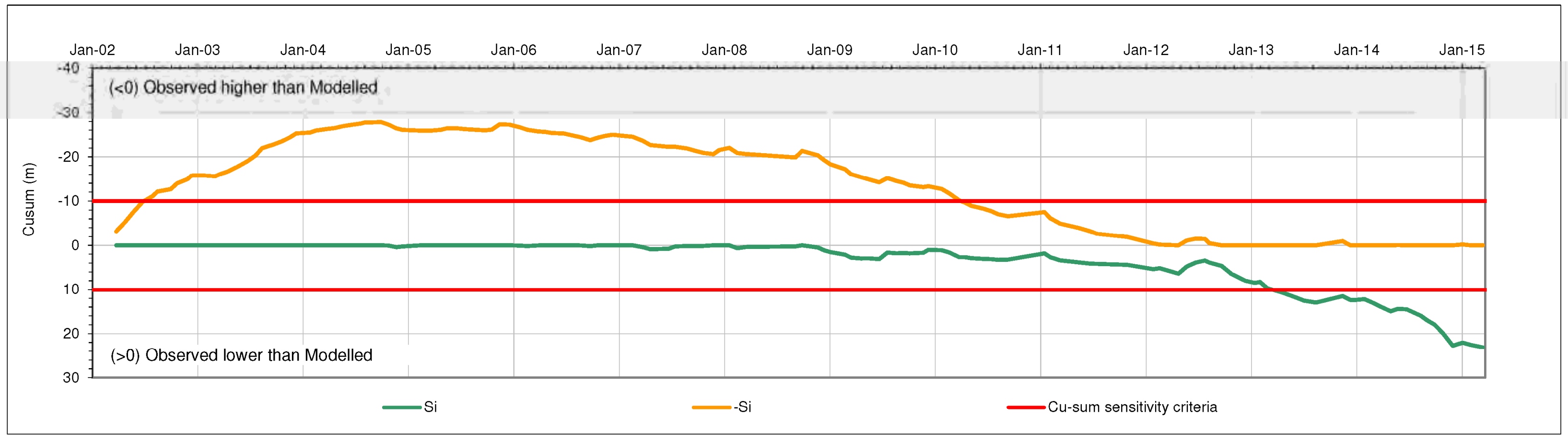
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**18416**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

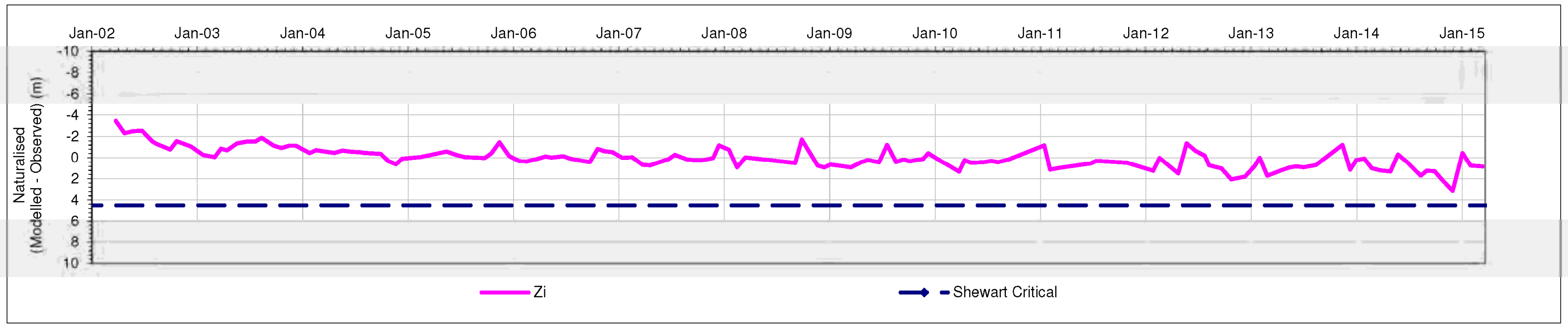
PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	





N.B. The scale on the cusum plot is larger than the CBACs standard (10 m, -10 m)



O:\6227_Cornelly\calcs\WMP supporting calcs\CBAC spreadsheets\E_new store 2015.xlsm Parameters

16/07/2015 08:55

Figure 3.1
Location E Climate Based Assessment Criteria calibration (all data used for statistics)

Date July 2015	Drawn KHB
Scale n/a	Checked MJS
Original A3	Revision 1
File Reference O:\6227\Reports\R17 EIA\Post submission WMP\Figures\Figure 3.1.doc	

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Runoff Calculation Parameters (Location E)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	5	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Rainfall station: Margam

Number of days 10682

General parameters **Head Change Calculation**

Rainfall Multiplier 1
PE Multiplier 1

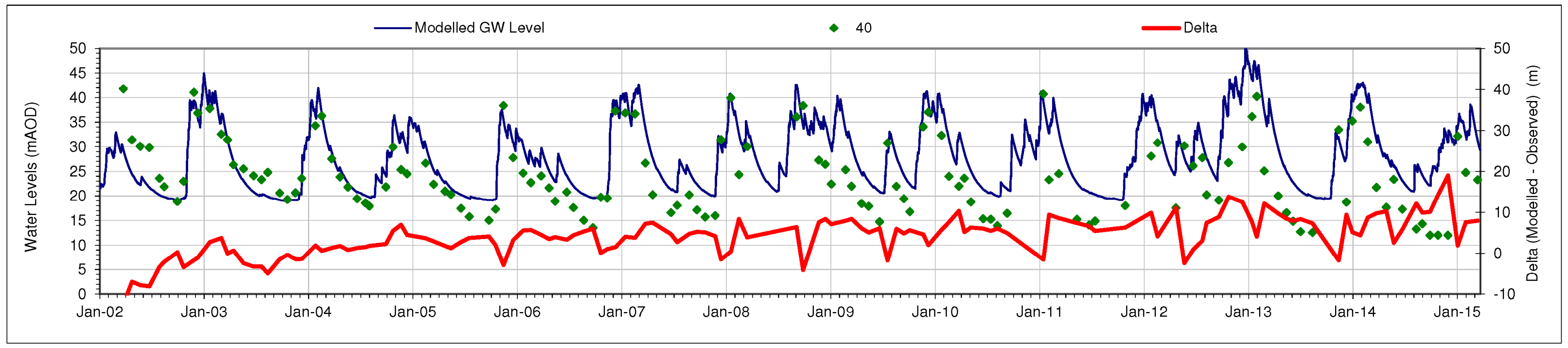
	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,420,082	0.007	18.5
GW	1,420,082	0.007 fracture	

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters

Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	70	%
T Slow	50	days
T Fast	50	days
Slow store max	100	mm



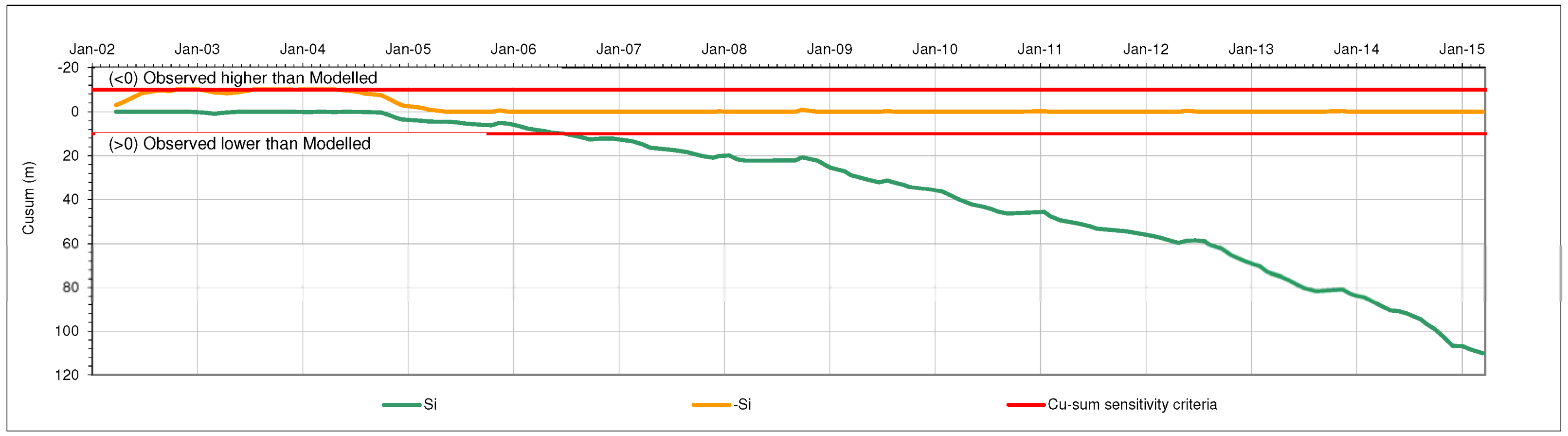
Stats

Baseline dataset for calculation of statistics:
March 2002 - July 2004

K (not permeability!!)	0.25	m
Mean Error (Modelled - Observed)	0.51	m
ST Dev Error	3.95	m
Dummy value for Z_i	0	

Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**18416**

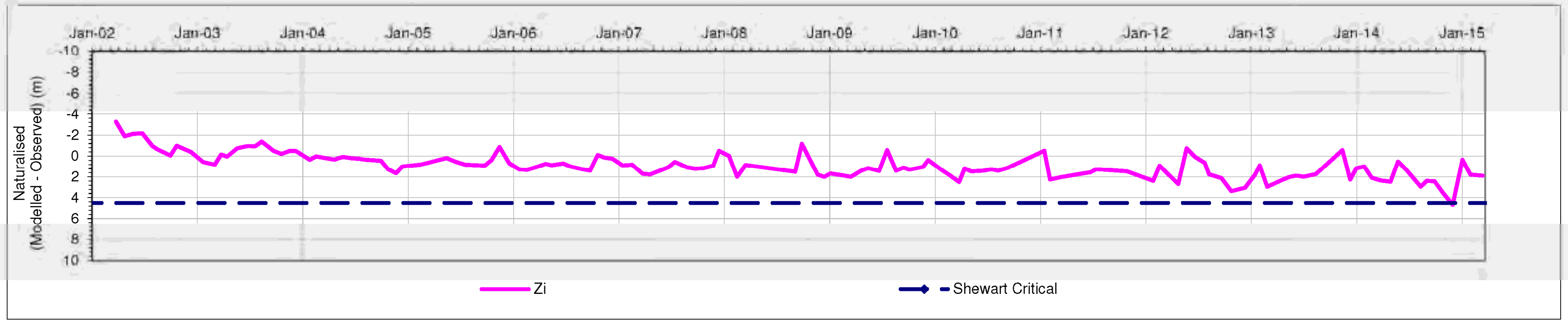
* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations



PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	

N.B. The scale on the cusum plot is larger than the CBACs standard (10 m, -10 m)



O:\6227_Cornelly\calcs\WMP supporting calcs\CBAC spreadsheets\E_new store 2015.xlsm Parameters

16/07/2015 08:53

Figure 3.2
Location E Climate Based Assessment Criteria calibration (baseline data used for statistics)

Date July 2015	Drawn KHB
Scale n/a	Checked MJS
Original A3	Revision 1
File Reference O:\6227\Reports\R17 EIA\Post submission WMP\Figures\Figure 3.2.doc	

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Runoff Calculation Parameters (Location South Cornelly)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3
SMD1_start (mm)	SMD2_start (mm)	
0	0	

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1	SW discharge
0	GW discharge

Number of days 10682

General parameters / **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.018	9.5
GW	1,756,799	0.018 fracture	

Rainfall Multiplier	1
PE Multiplier	1

User-defined time series

Precipitation (mm) - Sheet SMB calcs

Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters		
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	70	days
T Fast	70	days
Slow store max	160	mm

Stats

Baseline dataset for calculation of error statistics:
n/a

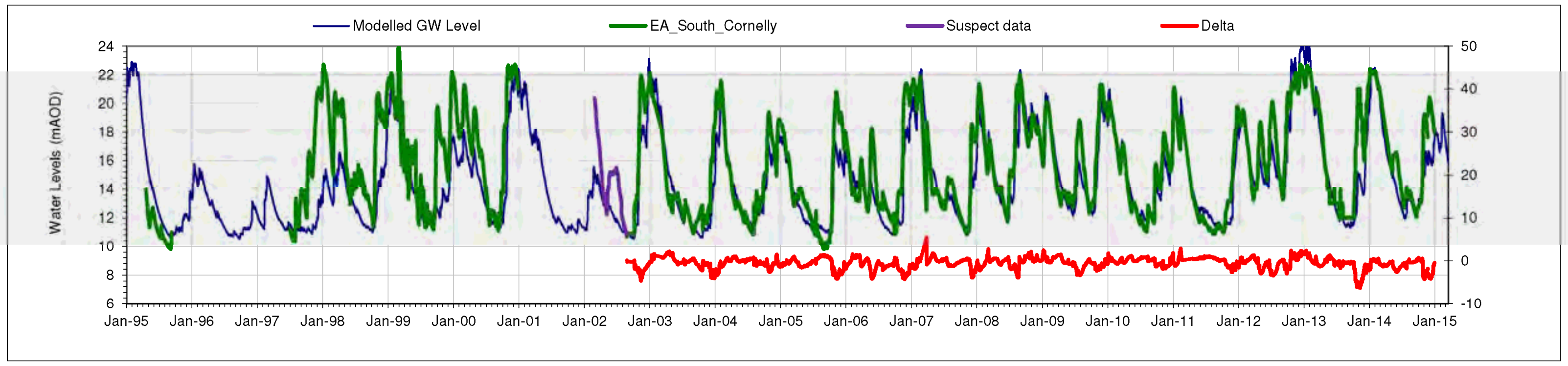
K (not permeability!!)	0.25 m
Mean Error (modelled - Actual)	-0.95 m
ST Dev Error	1.77 m
Dummy value for Z_i	0

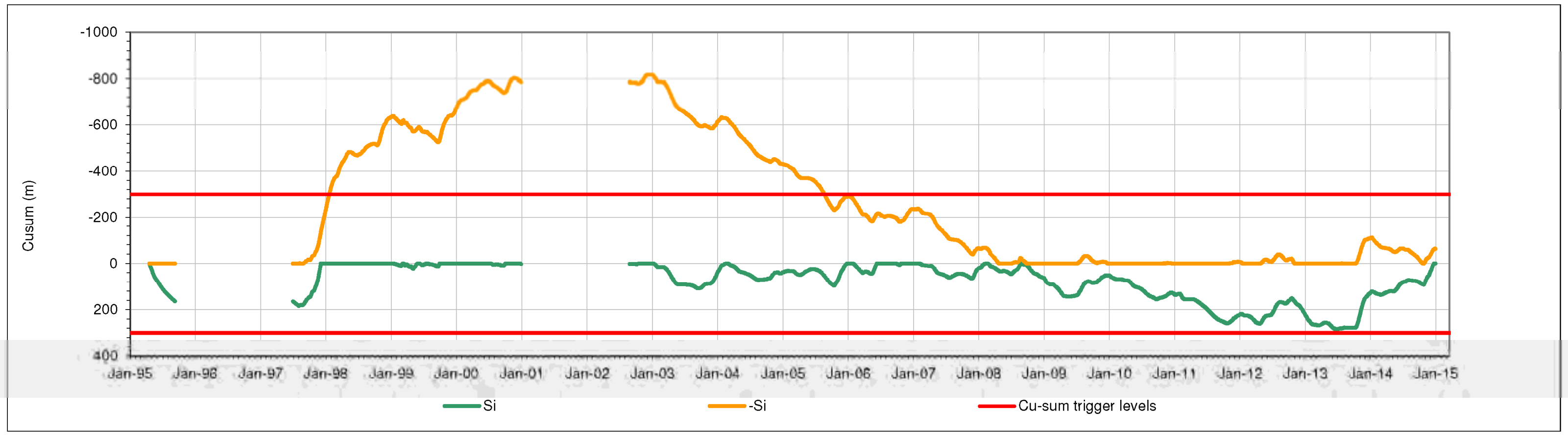
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**27022**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

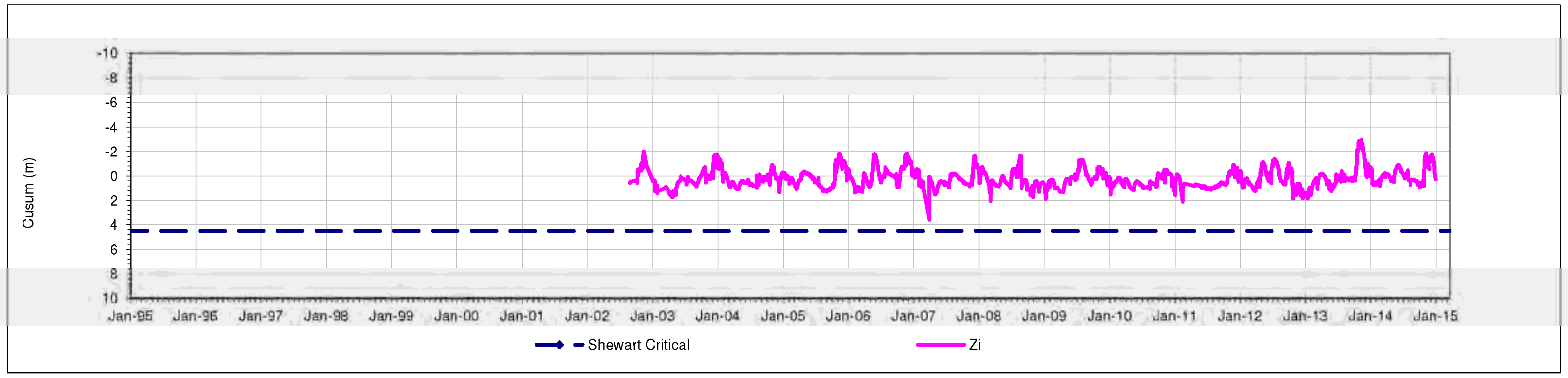
PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	





N.B. The scale on the cusum plot is larger than the CBACs standard (15 m, -15 m)



O:\6227_Cornelly\calcs\WMP supporting calcs\CBAC spreadsheets\South Cornelly_new store 2015.xlsm Parameters

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Figure 3.3

South Cornelly Climate Based Assessment Criteria calibration (all data used for statistics)

Date July 2015	Drawn KHB
Scale n/a	Checked MJS
Original A3	Revision 1
File Reference O:\6227\Reports\R17 EIA\Post submission WMP\Figures\Figure 3.3.doc	

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Runoff Calculation Parameters (Location South Cornelly)

Parameters for Soil Moisture Balance

Drying constant (mm)	Direct percolation (%)	Drying curve slope
75	25	0.3

SMD1_start (mm)	SMD2_start (mm)
0	0

All Parameters provided

Runoff Parameters

SMD	5	30	
0	0	0	0
20	0	0	0

Rainfall station: Margam

GW Abstractions (Ml/d)

0

Slow flow split

1 SW discharge
0 GW discharge

Number of days 10682

General parameters **Head Change Calculation**

	Catchment_Area (m2)	Specific_Yield	Starting_Head (mAOD)
SW	1,756,799	0.018	9.5
GW	1,756,799	0.018 fracture	

Rainfall Multiplier 1
PE Multiplier 1

User-defined time series

Precipitation (mm) - Sheet SMB calcs
Potential evapotranspiration (mm) - Sheet SMB calcs

Stores Parameters		
Runoff multiplier	0	
Slow store Starting Volume	0	mm
Fast store Starting Volume	0	mm
% Slow	100	%
T Slow	70	days
T Fast	70	days
Slow store max	160	mm

Stats

Baseline dataset for calculation of error statistics:
September 2002 - January 2013

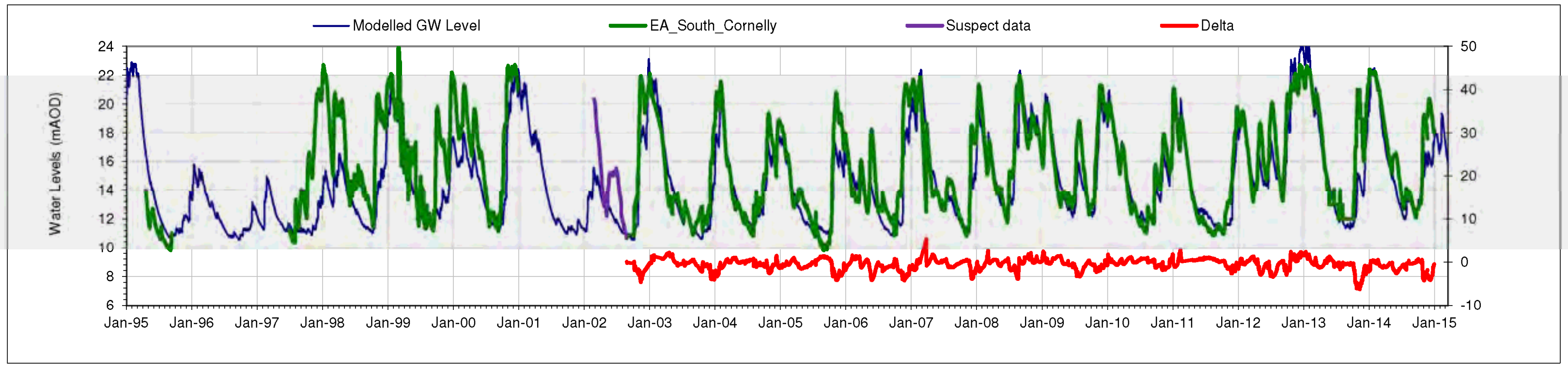
K (not permeability!!)	0.25	m
Mean Error (modelled - Actual)	-0.51	m
ST Dev Error	1.24	m
Dummy value for Z_i	0	

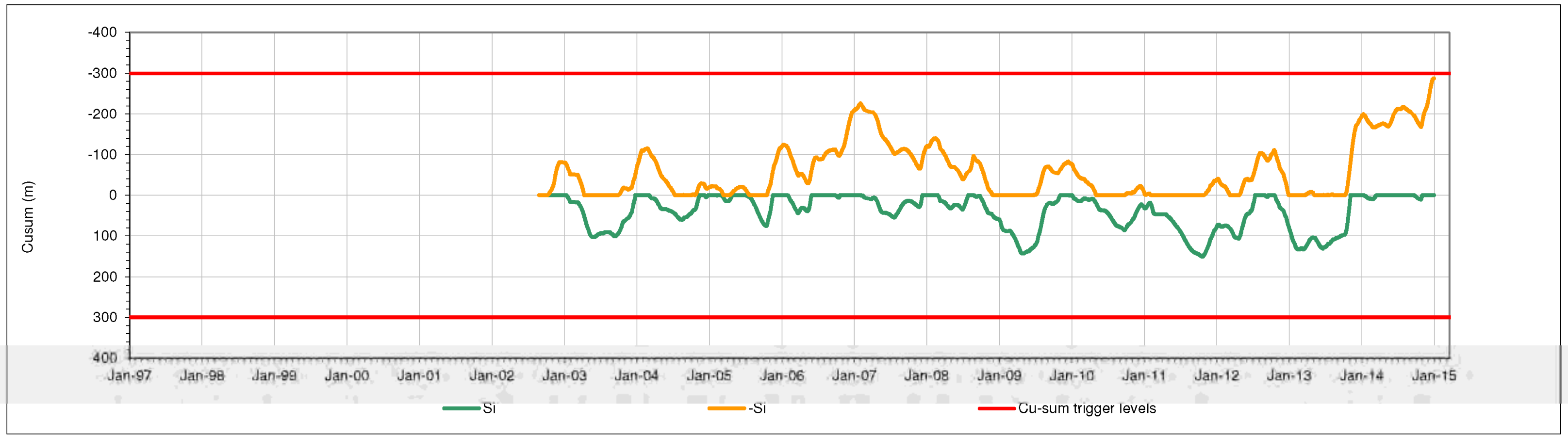
Phi_calibration - last loaded PEST run	**n/a**
Phi_calibration - spreadsheet calcs	**27022**

* If PEST is used, PEST and spreadvalues should be equal, showing consistant calculations

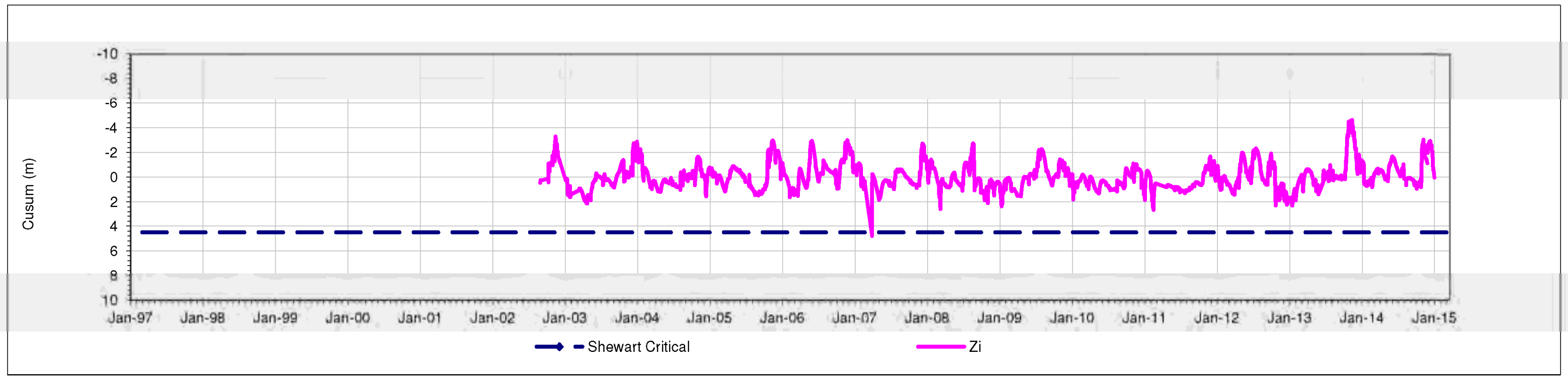
PEST weightings

Default weight for minimum annual values	20.0
Default weight for maximum annual values	10.0
Default standard weight is 1.0	





N.B. The scale on the cusum plot is larger than the CBACs standard (15 m, -15 m)



O:\6227_Cornelly\calcs\WMP supporting calcs\CBAC spreadsheets\South Cornelly_new store 2015.xlsm Parameters

16/07/2015 08:58

Figure 3.4
South Cornelly Climate Based Assessment Criteria calibration (baseline data used for statistics)

Date July 2015	Drawn KHB
Scale n/a	Checked MJS
Original A3	Revision 1
File Reference O:\6227\Reports\R17 EIA\Post submission WMP\Figures\Figure 3.4.doc	

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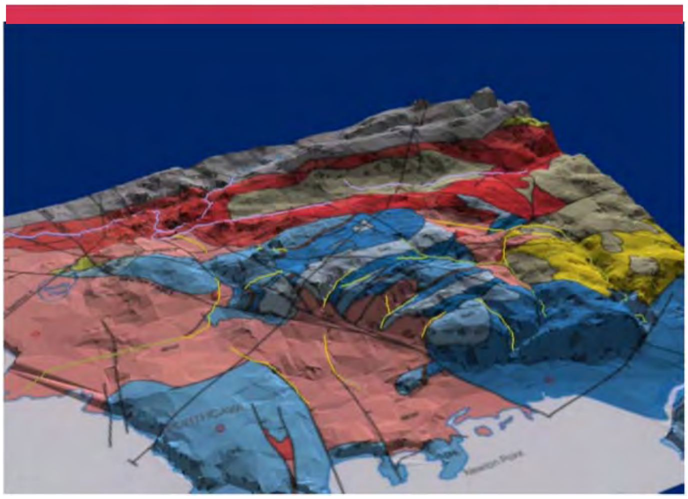
APPENDIX E
Flow Network Model
(Appendix 7.3 from SLR, 2014)



Cornelly Group of Quarries: Transient Flow Network Model

Cornelly Group of Quarries: Transient Flow Network Model

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Report reference: 6227 Appendix 7.3, March 2014
Report status: Final

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Cornelly Group of Quarries: Transient Flow Network Model

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6227 Appendix 7.3. Final

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Checked by	Barnaby Harding		04/03/14	Project Team
Reviewed by	Mike Streetly		04/03/14	Project Team

Revision record:

Issue	Date	Status	Comment	Author	Checker	Reviewer
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2						
3						
4						

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CONTENTS

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ILLUSTRATIONS

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1 INTRODUCTION

This technical appendix describes the development, calibration and use of a transient flow network model which has been developed to support the assessment of the potential effects of the future development of the Connelly Group of Quarries on the local hydrology.

1.1 Background

In the first hydrogeological impact assessment report for Cornelly Quarry (ESI, 2004), a complex steady state "groundwater flow network model" was developed. The model was almost entirely designed to simulate bedrock groundwater flow with the exception of a cell representing the sand and gravel layer which lies beneath the Blown Sands at Kenfig.

Due to the limitations of the groundwater flow network model, additional detailed calculations were undertaken to determine the impact of changes in groundwater level and flow on the Blown Sand aquifers at Kenfig and Merthyr Mawr. The conclusions from these detailed calculations were as follows:

- At Kenfig: Drawdowns of between 4.6 and 6.1 m are required in the sands and gravels in order to induce an average 0.1 m change in head (the sensitivity threshold identified by CCW (now NRW)) in the dunes over the period.
- At Merthyr Mawr: Reduction in inflows from the north would need to be greater than 5% (probably around 10%) to induce a 0.1 m change in average summer groundwater level.

Subsequent discussions with NRW for the current phase of work have identified a need to assess transient aspects of dewatering at the Cornelly group of quarries (the rate at which the effects of a sudden increase in abstraction would transmit away from the quarries, the effects and duration of recovery at the end of pumping) and also an incorporation of the variation in hydrogeological conditions at Kenfig and Merthyr Mawr.

In order to do this it has been decided to adapt the existing groundwater flow network model to work in transient mode and also to directly simulate conditions at Kenfig and Merthyr Mawr through the incorporation of additional model cells. The updated model construction and results are described in the following sections.

1.2 Structure of this Document

The planning context etc. is described in the main Environmental Statement. The conceptual model on which the model is based is described in Appendix 7.1 of the Environmental Statement.

After this introduction, Section 2 describes the transient flow model in detail. Section 3 describes the model calibration whilst Section 4 explains how the predictive scenarios were set up. The results of the predictive scenarios are set out in Appendix 7.4.

2 MODEL DESCRIPTION

2.1 Modelling Approach

The model has been developed as an Excel spreadsheet and VBA code, and designed to simulate daily time series for groundwater heads and discharges.

Modelling is undertaken using explicit timestepping and changes in groundwater levels in each zone are derived from recharge, from groundwater flows between connected zones and discharges to boundary conditions (either to springs, drains, dewatering abstractions or the sea).

2.2 Model Zones

Model zones were defined on the basis of the conceptual model (Appendix 7.1) and are broadly consistent with the areas represented in the steady state model undertaken in a previous assessment (ESI, 2004). These zones were further subdivided to represent the areas around the quarries (to allow a more accurate assessment of the quarry inflows and outflows) in addition to refinement and layering around Kenfig dunes and Merthyr Mawr.

A schematic representation of the model zones used in the simulations is shown on Figure 2.1 and is described in more detail in the following sections.

2.3 Recharge

The derivation of the recharge input for the model is described in the Conceptual Model Report (Appendix 7.1). It is based on the soil moisture balance approach previously used at Cornelly both for the conceptual model (Appendix 7.1) and for the water Management Plan (Climate based assessment criteria).

Daily recharge values in the model are spatially distributed between zones to correspond with the sites for which the recharge input calculations were undertaken (see some discussion on different areas in Appendix I of Appendix 7.1). The rate at which water allowed to recharge the groundwater system is therefore determined by the recharge values and the area of each model zone.

The change in groundwater flux due to recharge $\Delta Q_{rec,j}$ in each j'th zone at time t is calculated from:

$$\Delta Q_{rec,j} = (1 - \alpha_j).R_{j,t}.\mathrm{A}_j.$$

where $\propto$ is fractional runoff(-),

R is recharge (m/day),

A is the zone area (m^2)

When the quarry is restored to open water there is the potential that the rate of evaporation will be different from that assumed in the recharge model. The degree of difference is hard to quantify as, although (for equivalent climatic conditions) the evaporation rate from open water is typically higher than for grass (the assumption of the recharge model), the rate of potential evaporation is very dependent on sunshine, humidity and wind speed. In a deep, steep sided quarry it is very likely that sunshine and wind speed (which promote evaporation) will be lower and humidity (which reduces evaporation) will be higher. It is thus possible that the potential evaporation rate at the water surface will be lower than would be assumed by standard calculations.

However, in order to assess the potential significance of this uncertainty, the recharge model has been re-run in a way that simulates the effects of open water whilst ignoring the effect of the factors discussed above. The results of this model are as follows:

Recharge rate (grass) 822 mm/a (average for period 1993 To 2003)

Recharge rate (open water) 719 mm/a (average for period 1993 To 2003)

Difference 103 mm/a.

Applying this difference over the potential area of open water (~25 ha) suggests an equivalent abstraction rate of around 70 m3/d. This effective abstraction rate is very small relative to current and predicted dewatering rates in the quarry and is not likely to have any discernible effect on the regional groundwater flow system. On this basis it has not been considered further in the modelling.

2.4 Discharge

The model allows for discrete discharges (e.g. local abstractions) to be input as time series for each zone over the duration of the simulation. By default discharges are input as -ve. Water can also be added to each zone using +ve values. Change in groundwater flux in each j'th zone due to discrete discharges $\Delta Q_{dis,j}$ at time t is calculated from

$$\Delta Q_{dis,j} = D_{j,t}$$

where D is discharge at time t (m^3/day)

2.5 Connectivity

The connection of the groundwater system is modelled as a series of zones representing the saturated zone in the main formations in the area. The saturated zone acts to transfer groundwater down hydraulic gradient between each zone.

The total groundwater flow between each j'th zone from each i'th zone at time t ($\Delta Q_{\sum i,j}$) is calculated from:

$$\Delta Q_{\sum i,j} = \sum_{i=1}^{N_{zone}} (h_{t-1,j} - h_{t-1,i}).\frac{T_{i,j}.w_{i,j}}{x_{i,j}}$$

where $h_{t-1,j}$ is the groundwater head from the previous timestep (m),

$T_{i,j}$ is the transmissivity between each zone (m^2/day),

$w_{i,j}$ is the flow width (m),

$x_{i,j}$ is the flow distance (m).

As more than one geology type may be described between nodal points and each flow path, the transmissivities are calculated using a harmonic mean approach (see Illustration 2.1).

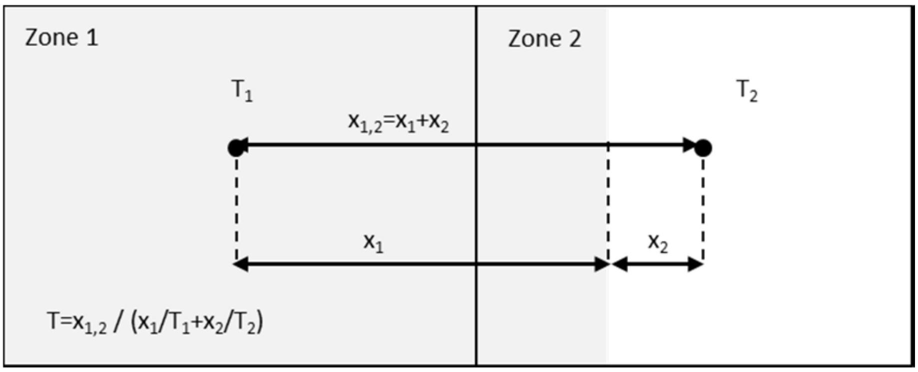


Illustration 2.1 Calculation of bulk transmissivity

The resulting transmissivity between each i'th and j'th zone is defined as:

$$T_{i,j} = x_{i,j} \;/\; \sum_{k=1}^{N_{trans}} \frac{x_k}{T_k}$$

where $x_{i,j}$ is the distance between zones (m),

x_k is the distance across a particular geology type (m),

T_k is the transmissivity of a particular geology type (m^2/day),

Parameterisation of the transmissivity of individual formations is discussed in Section 3.3.

2.5.1 Variation of hydraulic conductivity with depth (VKD)

An additional complication in the estimation of transmissivity is the concept of variable hydraulic conductivity with depth (or VKD). This is consistent with both the description of palaeokarst in the area (Appendix H of Appendix 7.1) and a review of the groundwater level information (see Section 3.3.2). The implementation of the VKD element in the model comprises up to three distinct hydraulic conductivity layers (see Illustration 2.3).

If deemed appropriate, transmissivity between each zone can be replaced with the VKD representation. VKD is recalculated at the beginning of each timestep using the previous estimates of groundwater head. Parameterisation of this feature is set out in Section 3.3.2.

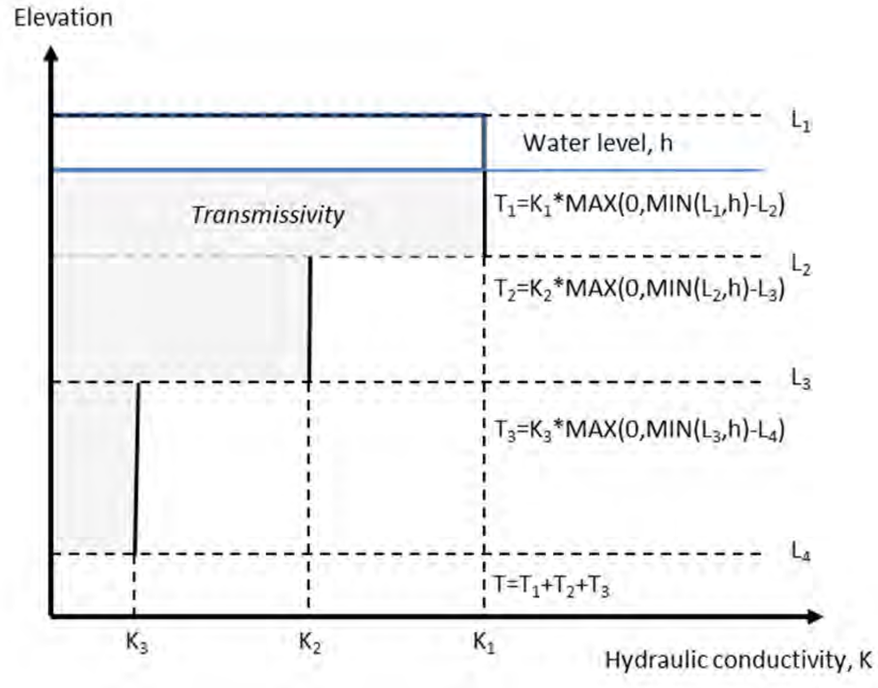


Illustration 2.2 Calculation of VKD

2.5.2 Vertical flow

The model allows for the incorporation of intervening layers between model zones (to represent a low hydraulic conductivity layer such as till for example). These intervening layers are not explicitly modelled (they are not a zone for which a groundwater head is computed).

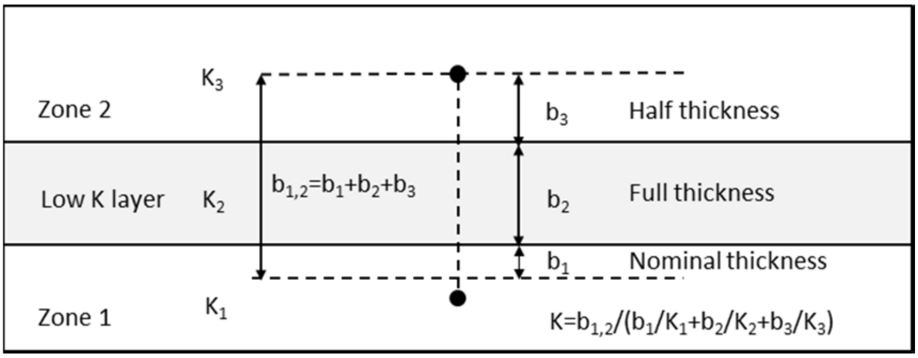


Illustration 2.3 Calculation of vertical hydraulic conductivity

The resulting hydraulic conductivity is calculated using the harmonic mean (see Illustration 2.3). This is calculated using a nominal thickness of the bottom layer (1m), the full thickness of the intervening layer and the half thickness of the overlying layer.

$$K_{\mathrm{ver,i,j}} = \mathrm{b}_{i,j} \ / \sum_{k=1}^{N_{cond}} \frac{b_k}{K_k}$$

where $K_{\mathrm{ver,i,j}}$ is the vertical hydraulic conductivity between zones (m/day),

$\mathrm{b}_{i,j}$ is the distance between zones (m),

b_k is the distance across a particular layer (m),

K_k is the vertical hydraulic conductivity of the k'th layer (m/day),

Apart from the interaction between these cells being vertical, the mathematics is similar as for the other cells. Vertical flow $\Delta Q_{ver,i,j}$ is calculated as:

$$\Delta Q_{ver,i,j} = (h_{t-1,j} - h_{t-1,i}).\frac{K_{ver,j}.A_j}{b_j}$$

where $h_{t-1,j}$ is the groundwater head from the previous timestep (m),

b_j is the thickness between zones (m).

2.6 Boundary Conditions

2.6.1 General head boundary

Discharges to downstream boundaries, such as the sea, are simulated using a general head boundary. The change in groundwater flow in each j'th zone due to flow to the general head boundaries ($\Delta Q_{ghb,j}$) are determined using:

$$\Delta Q_{ghb,j} \ = -(h_{t-1,j} - h_{ghb,j}).\frac{T_{ghb,j}.w_{ghb,j}}{x_{ghb,j}}$$

where $h_{ghb,,j}$ is the head assigned as the boundary value in each zone(m),

$T_{ghb,j}$ is transmissivity along the flow path to the general head boundary (m^2/day),

$w_{ghb,j}$is the width along the flow path to the general head boundary (m),

$x_{ghb,j}$ is the distance to the general head boundary (m).

2.6.2 Spring

A similar expression can be used to represent spring flows, although discharge is subject to a head constraint. The spring is only active if the heads exceed the spring elevation. Spring discharge $\Delta Q_{spr,j}$ from each j'th zone are determined using:

$$\Delta Q_{spr,j} = (h_{t-1,j} - h_{spr,j}).\frac{T_{spr,j}.w_{spr,j}}{x_{spr,j}} \qquad if\ h_{t-1,j} > h_{spr,j}$$

$$\Delta Q_{spr,j} = 0 \qquad if\ h_{t-1,j} \leq h_{spr,j}$$

where $h_{spr,,j}$ is the head assigned as the spring boundary value in each zone(m),

$T_{spr,j}$ is transmissivity along the flow path to the spring (m^2/day),

$w_{spr,j}$ is the width along the flow path to the spring (m),

$x_{spr,j}$ is the distance to the spring (m).

Spring transmissivity can be specified using a fixed value, or use dynamic values calculated using VKD.

2.6.3 Drain

The drain boundary condition is used to simulate overtopping, for example where Kenfig Pool has been observed to overtop and flow westwards into the dune slacks during periods of high groundwater levels.

A volume of water in a store above drain elevation $\Delta Q_{dra,j}$ is removed from the model as drain flow.

$$\Delta Q_{dra,j} = -(h_{t-1,j} - h_{dra,j}).\mathrm{A}_j.S_j/\Delta t \qquad if\ h_{t-1,j} > h_{dra,j}$$

$$\Delta Q_{dra,j} = 0 \qquad if\ h_{t-1,j} \leq h_{dra,j}$$

2.6.4 Sump

Flow calculations were modified in the vicinity of the quarries, where the mass balance equations do not take into account radial flow. A tractable approach is to use the analytical equation of unconfined radial flow to a well. Flow is established from the head difference at two radial distances from the sump. If we assume that these heads (sump levels and head at a given radius from the sump) are constant over one timestep the flow field will be radial. Under this assumption, radial flow through any 'cylinder' must be identical to the sump dewatering rate $\Delta Q_{sum,j}$. This is effectively the unconfined Thiem-Dupuit radial flow equation for groundwater flow toward the pumping wells:

$$\Delta Q_{sum,j} = \frac{\pi.K_{h,j}.((h_{t-1,j} - \mathrm{b}_j)^2 - (s_{t-1,j} - \mathrm{b}_j)^2)}{2.3.\log(r_{h,j}/r_{s,j})}$$

where h_j and s_j are the zone and sump head respectively (m),

$r_{h,j}$ and $r_{s,j}$ are the zone and sump radius respectively (m),

b_j is the base of the aquifer (m),

$K_{h,j}$is the horizontal hydraulic conductivity (m/day),

The sump head represents the dewatered level (the sump level) within the quarry itself (considered to extend 10 m below the base of the lowest working bench level) provided as a time series representing the quarry development. The zone head is representative of groundwater heads at a given radius outside of the immediate quarry boundaries, calculated for each zone in which active dewatering is occurring.

Hydraulic conductivity was limited to the zone of active aquifer in the vicinity of the quarry sump (up to the zone groundwater water level predicted by the model). This assumes that most of the groundwater inflow to the quarry sump occurs laterally rather than vertically. Depth dependent hydraulic conductivity can be accounted for by simple averaging.

2.6.5 Boundary condition re-direction

All spring, drain and sump flows can be routed to discharge to other model zones. For example, to simulate pumping from quarries, or discharge from springs into other areas. The discharge ΔQ_{red} is implemented at each timestep using spring, drain or sump flows from the preceding timestep.

Flows can be redistributed according to fixed proportions (i.e. part of each flow can be redistributed to more than one zone). The model also allows flows to be redistributed according to a series of logic statements. The logic statements work in combination with the concept of 'additional storage' (see Section 2.8) in which redirection to several zones can be simulated based on the volume of the additional storage.

2.7 Change in Storage

For each zone, the resulting change in storage is calculated from the sum of all inflows and outflows for each zone as:

$$\Delta Q_{sto} = \Delta Q_{rec} + \Delta Q_{dis} + \Delta Q_{\sum i,j} + \Delta Q_{ver} + \Delta Q_{ghb} + \Delta Q_{spr} + \Delta Q_{dra} + \Delta Q_{sum} + \Delta Q_{red}$$

2.8 Additional Storage

There are a number of features in the model area that may potentially contain significant volumes of water and may locally affect heads. For example, part of each model zone may include settlement lagoons, dune slacks and pools that may contribute to additional storage. This additional storage volume may also become active only when groundwater levels rise above a particular elevation (for example the sump level, or base of pool).

An additional storage area can be incorporate within each zone as shown in Illustration 2.4.

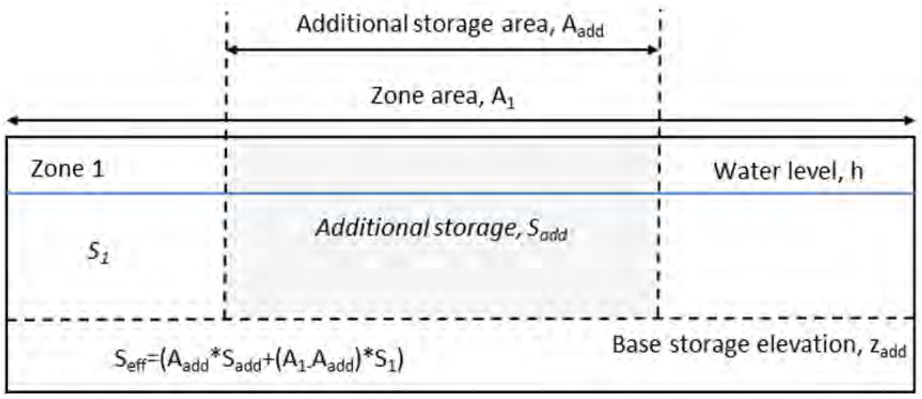


Illustration 2.4 Calculation of additional storage

The user needs to specify an additional storage area, the value of additional storage (i.e. 1.0 for open water) and the elevation above which this additional storage becomes active. Groundwater levels within each zone are still assumed to be constant and an effective storage $S_{eff,j}$. for each zone can be calculated when the set elevation is exceeded:

$$S_{eff,j} = (S_j(A_j - A_{add,j}) + S_{add,j}A_{add,j})/A_j \qquad if\ h_{t-1,j} > z_{add,j}$$

$$S_{eff,j} = S_j \qquad if\ h_{t-1,j} \le z_{add,j}$$

where $S_{add,j}$ is the additional storage (-),

$A_{add,j}$ is additional storage area (m^2).

2.9 Change in Groundwater Head

Following changes in storage from the sum of all inflows and outflows in each zone there is a response in groundwater levels. For each j'th catchment store the change in groundwater head (Δh_j) at time t is calculated from:

$$\Delta h_j = {\Delta Q_{sto,j}} \Big/ {S_{eff,j} . \text{A}_j} . \Delta t$$

The new head at time t is therefore:

$$h_t = h_{t-1} + \Delta h$$

2.10 Model Geometry

In order to address some of the concerns raised in previous consultations, the sand dunes in Kenfig and Merthyr Mawr have been explicitly represented in this model. Using the layered model the groundwater flow network model can be used directly to assess potential effects of additional quarry development on water levels within the dune systems. This required the addition of model cells at a scale appropriate to model potential impacts that effectively overlie the cells representing the 'solid' geology.

2.10.1 Kenfig

The conceptual model of the layered system at Kenfig is discussed in detail in the conceptual model report (Appendix 7.1) and can be broadly summarised as:

- The blown sand act as a fairly homogeneous system. They are fed by direct rainfall and discharge occurs laterally via groundwater flow to the coast and, to a lesser extent, via downwards leakage into the underlying geology;
- A series of glaciofluvial sands and gravels underlie the blown sand. Groundwater levels are generally lower and show distinctly different behaviour. This is believed to be due to an extensive intervening layer of low hydraulic conductivity estuarine clay that limits the connection between the dunes and the underlying sands and gravels;
- The extent of the estuarine clay underlying the blown sand and Kenfig Pool is uncertain;
- Glaciofluvial sands and gravels underlying the estuarine clay are fed by recharge in the area of outcrop (east of Kenfig Pool), groundwater flow (from potentially well-connected underlying geology) and leakage from the overlying formations;
- The glaciofluvial deposits/till around Borehole A acts as a minor, perched aquifer to feed the ephemeral springs that flow to Kenfig Pool.
- The glaciofluvial system is not well connected to the underlying 'solid geology' groundwater flow system around the south of the pool but appears to be in closer connection to the north east (borehole N).
- A low hydraulic conductivity till limits the connection between the sands and gravels and underlying solid geology, although the extent of this till layer is not certain. Connection between the sands and gravels and the coast may also be restricted by this till layer;
- Kenfig pool may receive some ephemeral inflows from seeps to the east. At high water levels the pool overflows to the south west.

Schematic illustrations of the Kenfig dune system demonstrating the model connectivity (and conceptual uncertainty in these connections) are shown in Illustration 2.5 to Illustration 2.12 below.

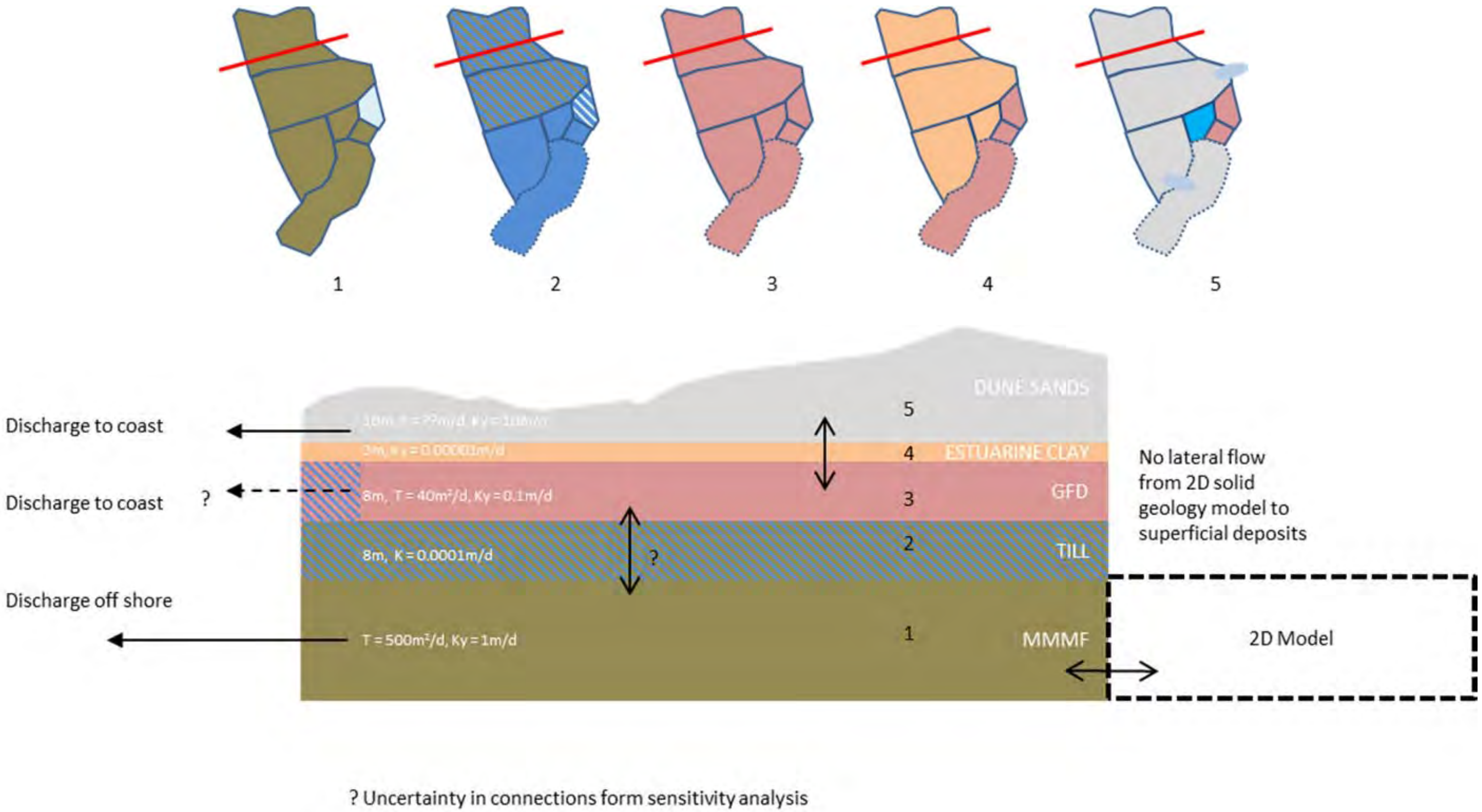


Illustration 2.5 Kenfig model section 1

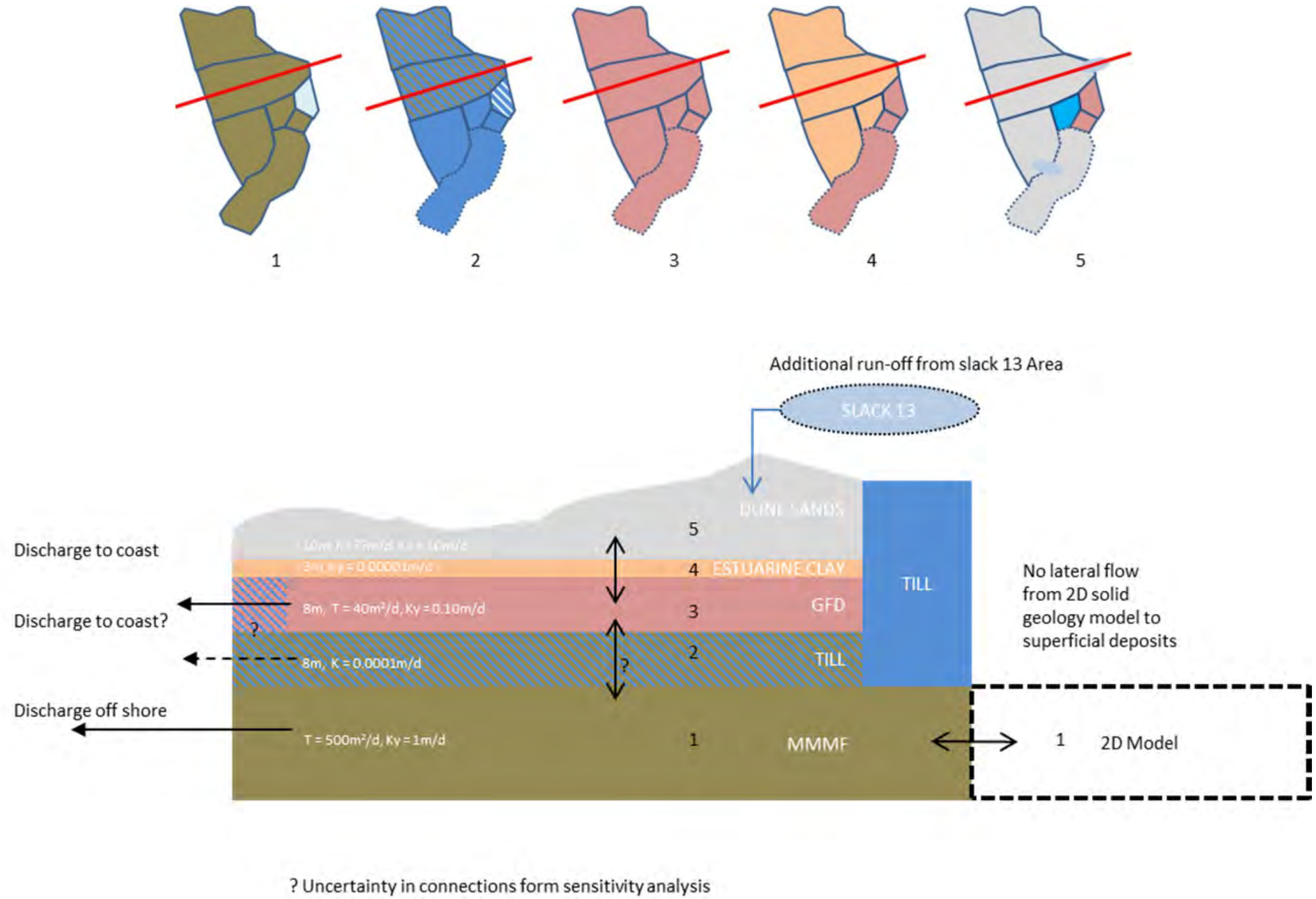


Illustration 2.6 Kenfig model section 2

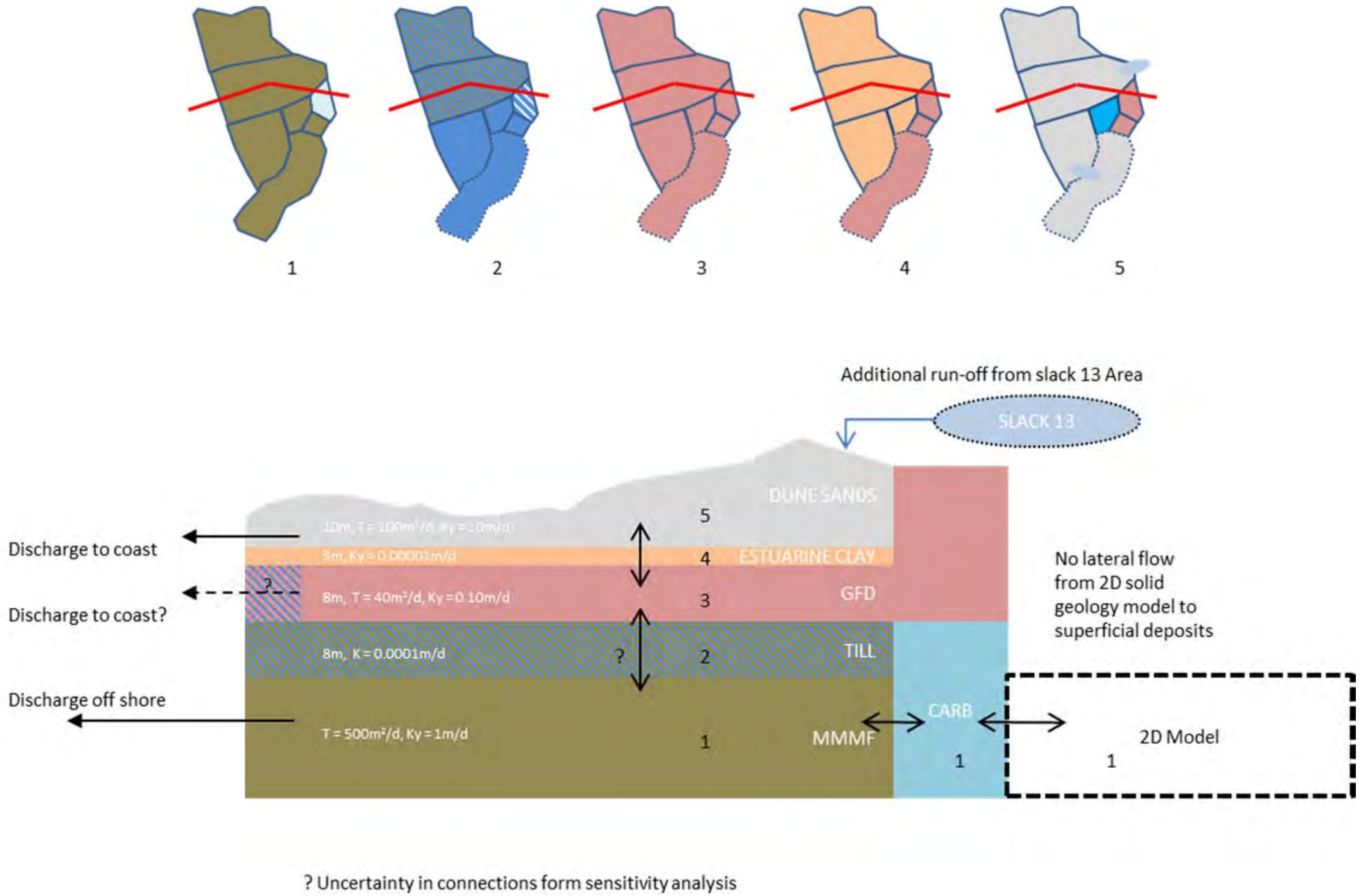


Illustration 2.7 Kenfig model section 3

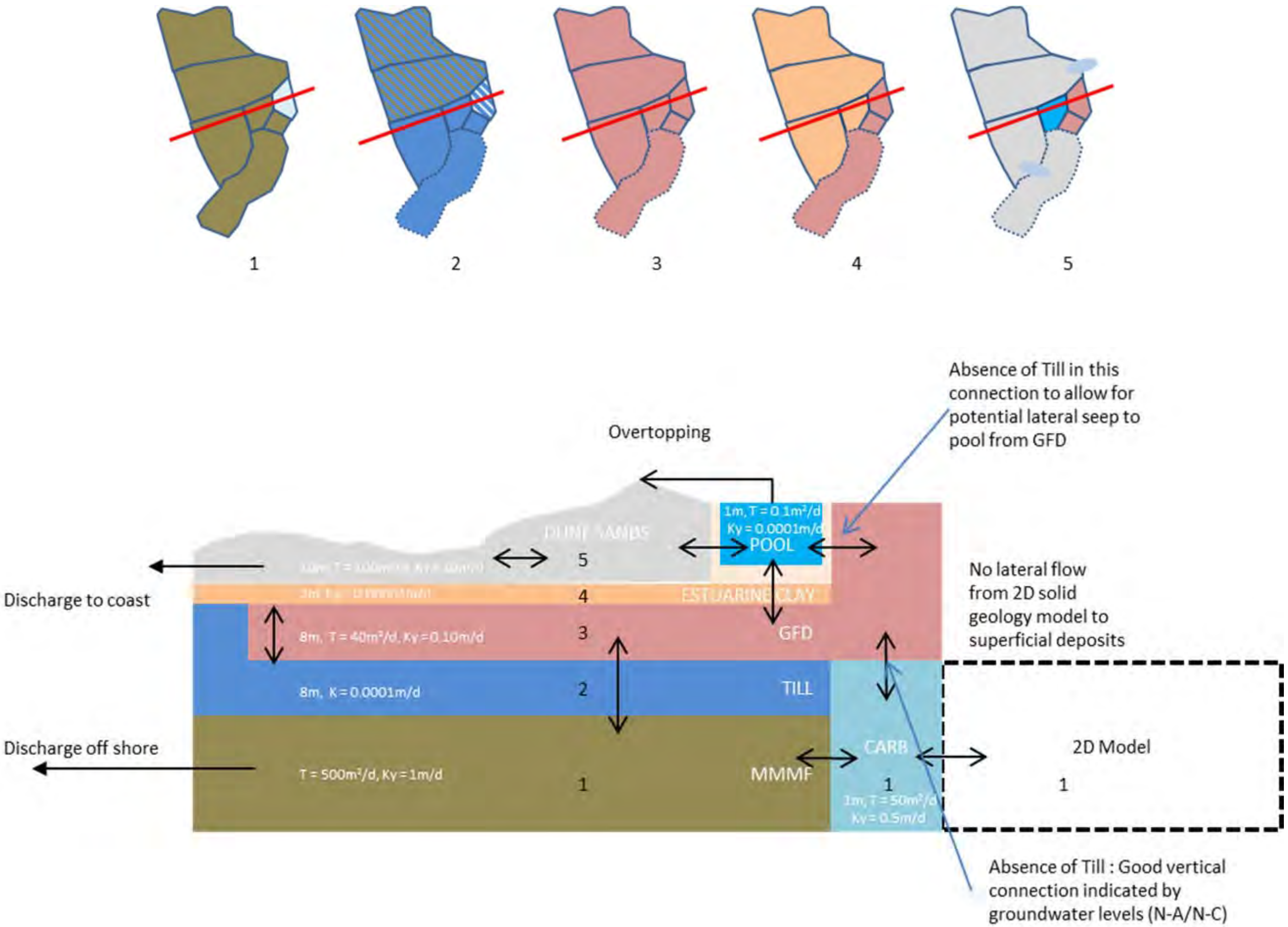


Illustration 2.8 Kenfig model section 4

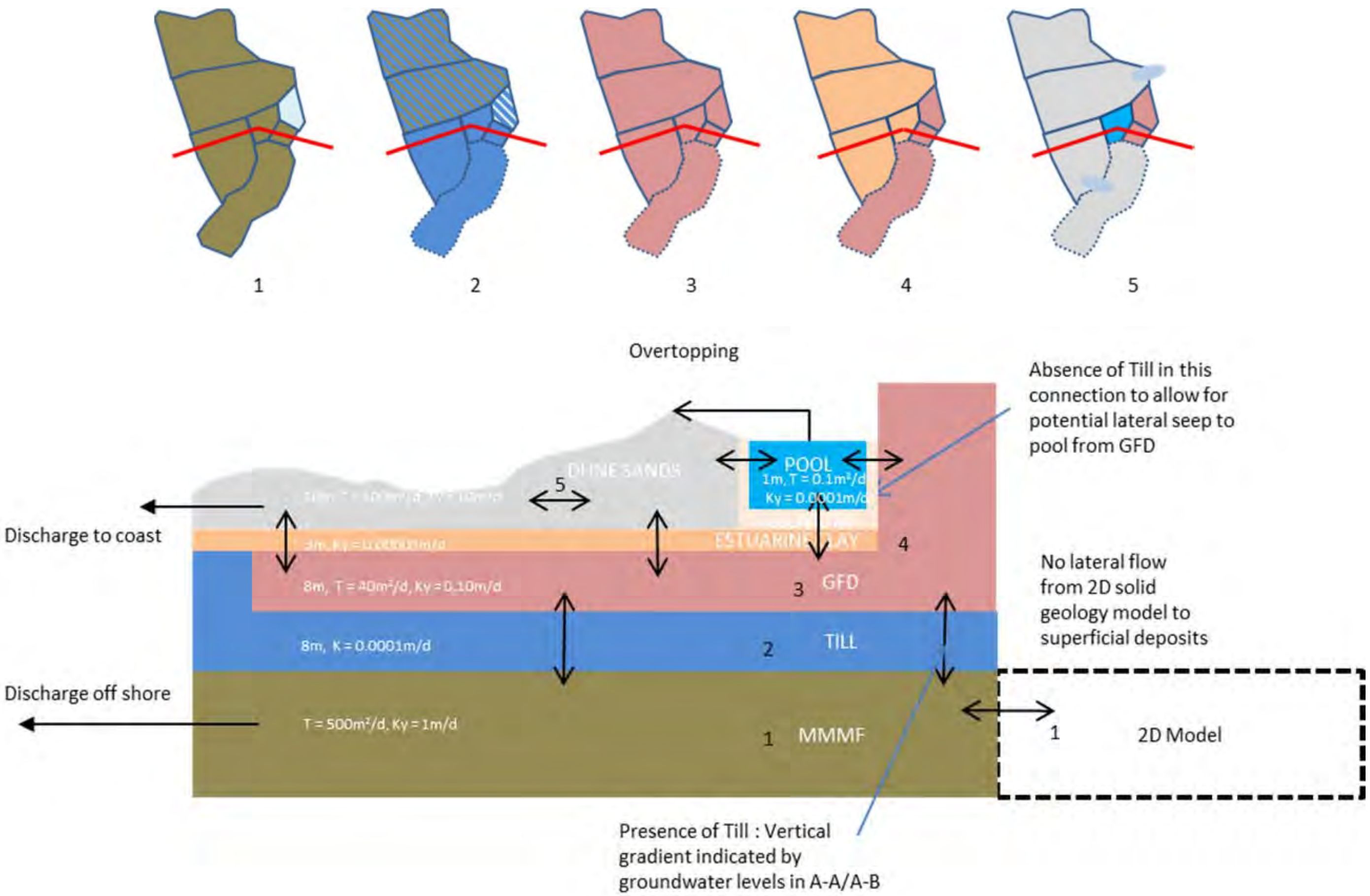


Illustration 2.9 Kenfig model section 5

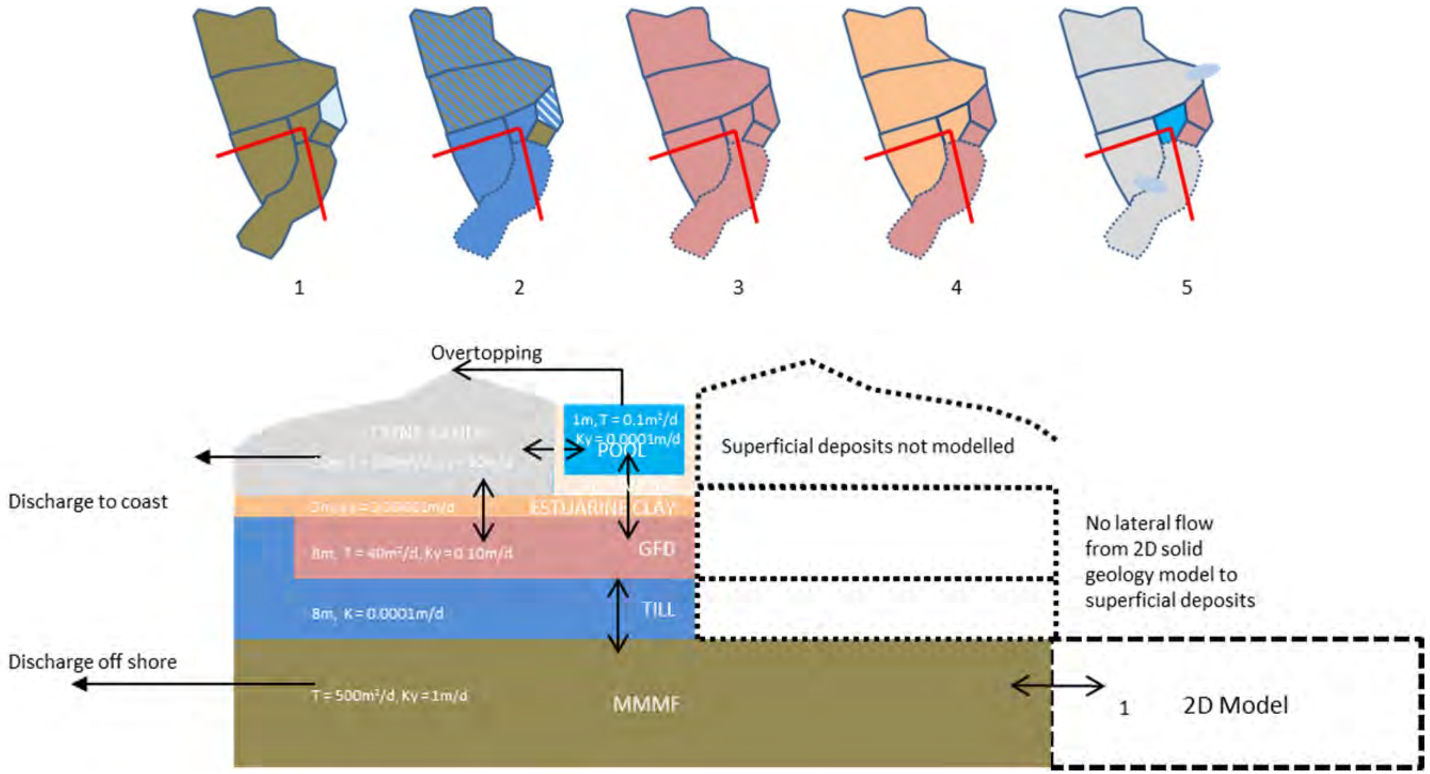


Illustration 2.10 Kenfig model section 6

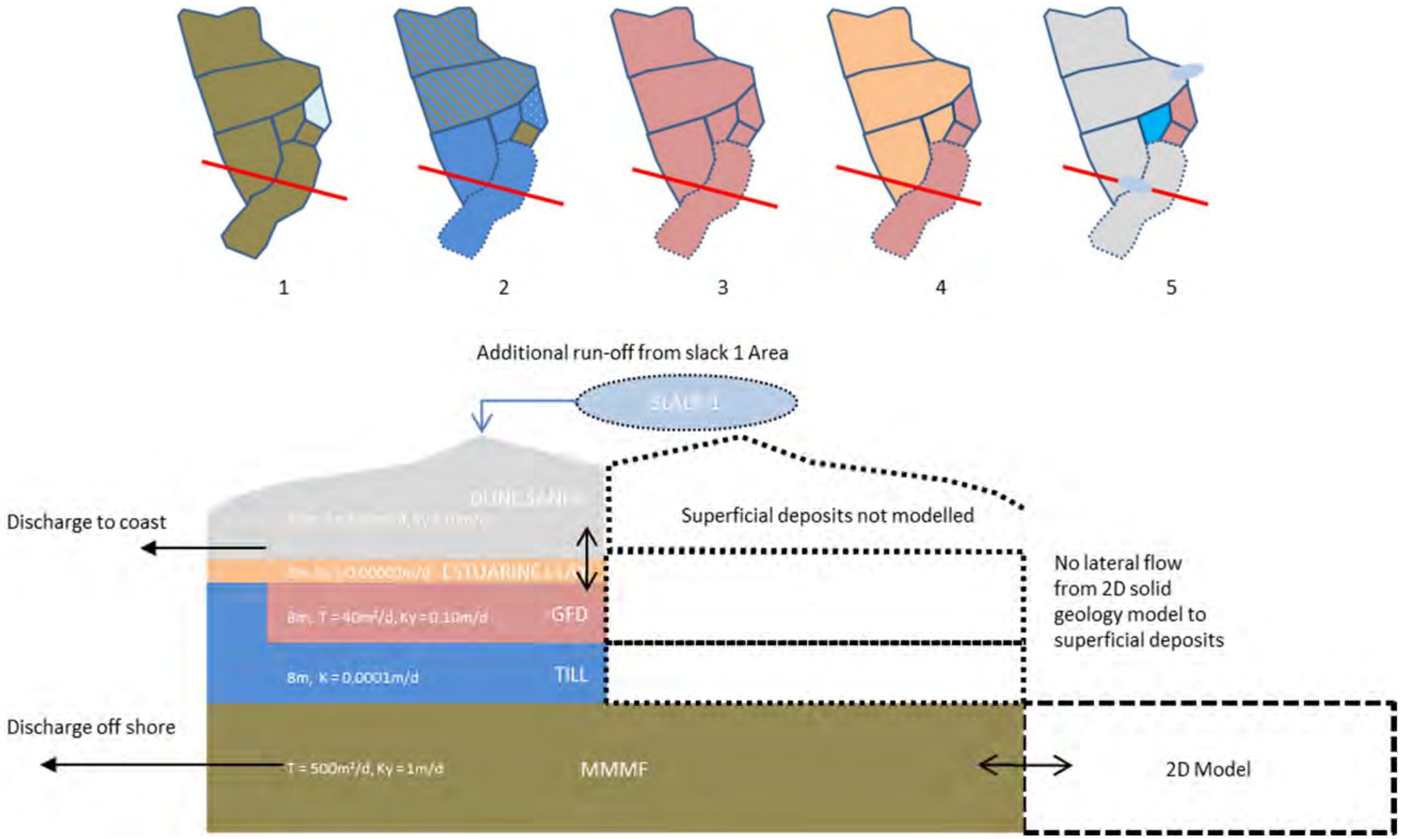
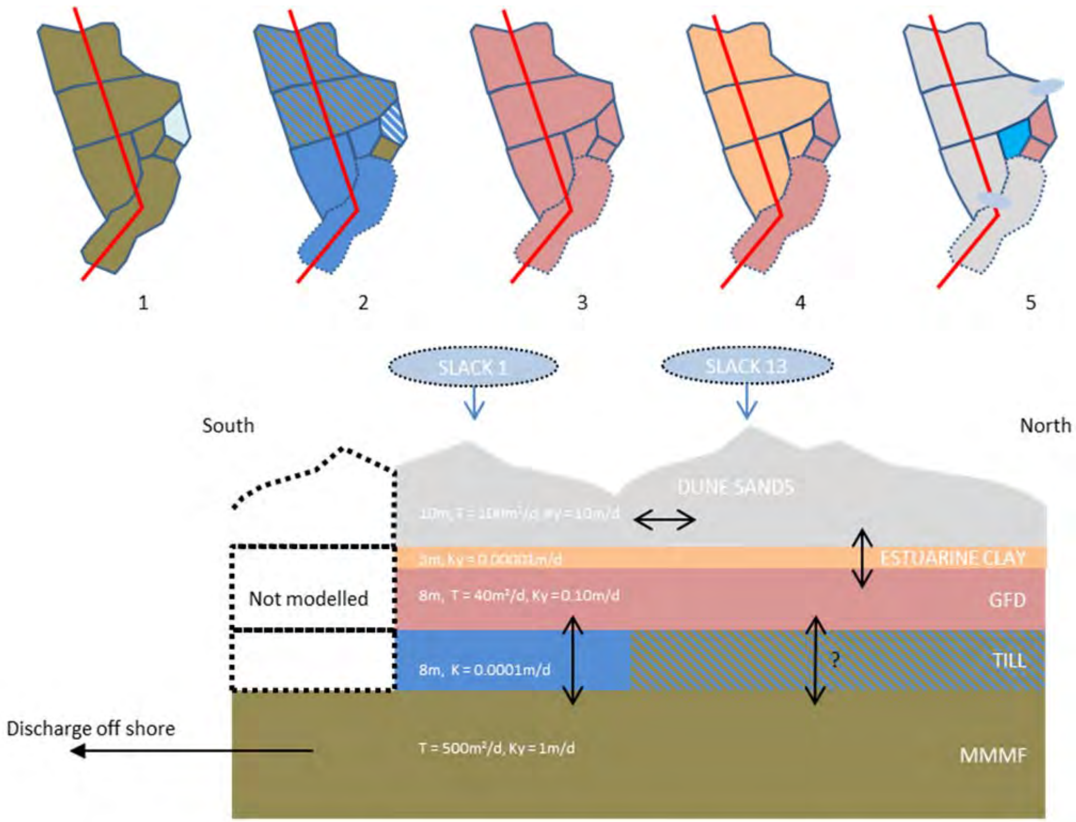


Illustration 2.11 Kenfig model section 7



? Uncertainty in connections form sensitivity analysis

Illustration 2.12 Kenfig model section 8

2.10.2 Merthyr Mawr

The conceptual model at Merthyr Mawr is discussed in detail in the conceptual model report (Appendix 7.1) and can be broadly summarised as:

- The blown sand receive direct recharge groundwater inflow from the Carboniferous Limestone (Burrows Well).
- Discharge in the blown sand occurs laterally via groundwater flow and overland via series of pool and dune slacks to the coast.
- Discharge in the blown sand also occurs via downwards leakage. Connection between the dunes and the underlying limestone is via an extensive but thin (1 m) underlying clay layer;
- South of Burrows Well, water levels are affected by the discharge of limestone groundwater levels into the blown sand which causes large areas to pond.
- When the spring stops flowing, these water levels drop rapidly and the groundwater system in this area is not typical of dune slacks more generally. SWS, 2010 suggest that this area may be perched on a thin clay layer.
- Groundwater gradients are locally predominantly downwards from the blown sand to limestone.

A schematic illustration of the Merthyr Mawr dune system demonstrating the model connectivity is shown below.

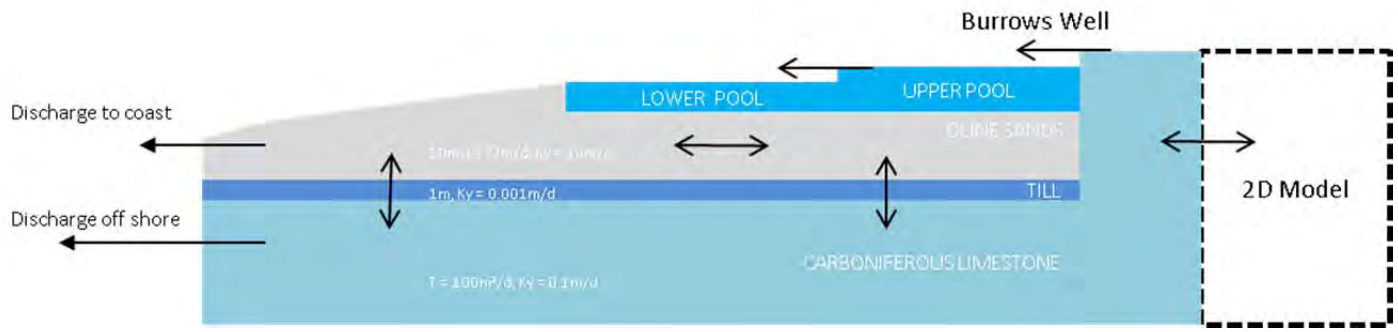


Illustration 2.13 Merthyr Mawr model section 1

3 MODEL CALIBRATION

3.1 Calibration Targets

The purpose of model calibration is to adjust certain model parameters (transmissivity, storage, etc.) within credible ranges in order to derive a close correlation between observed and simulated conditions. In this case, the model has been calibrated to the following targets:

- observed groundwater levels (including assessment of likely groundwater levels at Cornelly prior to the start of dewatering),
- observed flows at New Mill Farm springs,
- observed flows at Burrows Well, and
- dewatering flows from within Cornelly quarry

Location of the calibration targets are shown in Figure 3.1.

3.1.1 Groundwater level targets

Thirty-two observation boreholes (summarised in Table 3.1) were selected as targets across the model area. Calibration targets were selected on the basis of location (ideally as close as possible to the centre of each zone), record length, frequency of measurement and perceived quality of the data.

Table 3.1 Calibration head targets

Borehole	X	Y	Count	From	To	Zone
TQ3	283070	179881	1662	16/06/1995	12/06/2013	1
ESP2	283025	179725	117	26/04/1999	18/01/2009	2
TM6	283905	179854	211	31/10/1994	12/06/2013	3/4
TM4	283718	180395	1566	08/11/1992	18/08/1999	5
RWC107	282883	179954	226	20/08/1998	07/06/2013	8
RWC105	282658	179886	163	20/08/1998	07/06/2013	9/18
G	284792	179502	122	17/10/2001	10/06/2013	10/20
T95/01	284304	179947	4235	22/09/1995	10/06/2013	11
T95/04	284099	180400	53	22/09/1995	27/11/2002	12
Q	282817	180984	102	22/10/2002	23/05/2013	14
E	282887	180499	118	25/03/2002	14/06/2013	15
17B	282137	180760	111	25/03/2002	23/05/2013	23
EASC	281757	180249	4876	20/04/1995	04/03/2012	24
N-A	280047	181714	100	02/12/2002	26/06/2013	25
RWC100	282187	179831	2345	12/08/1998	24/06/2010	26/27
40	281970	179600	118	24/04/2002	04/06/2013	28
ITUSCA	285104	178646	53	29/01/1998	22/05/2003	29
T	283825	179196	14	03/10/2012	02/10/2013	30
MM1	285602	176878	692	24/11/2009	14/10/2011	33
P	281848	181099	108	22/10/2002	27/06/2013	35
O-A	280473	182851	111	22/10/2002	05/06/2013	36
A-A	280206	181254	298	17/10/2001	12/06/2013	38
B-A	280564	180567	122	17/10/2001	04/06/2013	40
21	283050	178200	48	25/03/2002	24/01/2006	41
L	285059	177372	101	20/05/2001	10/06/2013	42/44
D7	285821	176834	71	01/03/2004	01/07/2013	43
D4	286253	176607	102	01/03/2004	01/07/2013	45
N-C	280047	181714	99	02/12/2002	26/06/2013	46
A-B	280206	181254	103	17/10/2001	12/06/2013	47
KP	279549	181172	4259	16/03/1999	30/11/2010	48/53
K1A	279348	181594	104	15/04/2003	26/06/2013	50
K1B	279348	181594	101	15/04/2003	26/06/2013	55
CC5	279202	182061	501	17/01/1986	01/06/2013	56

3.1.2 Spring flow targets

Location and available data for spring flow targets are summarised in Table 3.2.

Table 3.2 Spring flow calibration targets

Borehole	Location	X	Y	Count	From	To	Zone
Burrows Well		285650	177260	1596	02/01/2008	31/03/2013	32
New Mills Farm	HL9A2 HL9B	280638 280286	182941 182919	18	15/05/2002	06/06/2004	36

<u>New Mills farm</u>

No reliable continuous gauging data are available at New Mills Farm springs due to a combination of unstable river banks and irregular flooding from the Afon Kenfig (Appendix J of Appendix 7.1). Data available in December 2002 recorded a relatively constant flow of between 60 and 80 l/s, although the period of data recording is insufficient for the purposes of model calibration.

A limited number of spot flow measurements are available to estimate longer term flows at New Mills Farm Spring. The difference in spot gauging between HL9A2 (upstream) and HL9B (downstream) represents a 400 m reach along Afon Kenfig. These data are used to provide a general assessment of the magnitude of the flows at New Mills Farm. Clearly the use of this spot gauging also means that the total flow includes contributions from both sides of the reach and the limited data means that continuous and long term flows are not well constrained.

Table 3.3 Spot gauging data at New Mills Farm spring

	Spot gauging (HL9B-HL9A2)	
Date	**l/s**	**m^3/day**
15/05/2002	121	10454
10/06/2002	531	45904
11/07/2002	72	623
29/08/2002	135	11638
10/01/2003	317	27363
12/02/2003	235	20293
12/03/2003	389	33610
22/04/2003	95	8199
03/06/2003	268	23121
08/07/2003	101	8726
28/10/2003	98	8476
23/12/2003	120	10368
30/01/2004	175	15120
24/02/2004	251	21686
11/03/2004	235	20304
26/04/2004	250	21600
18/05/2004	62	5357
09/06/2004	32	2765

Burrows Well

A stream flow logger was installed on Burrows Well in January 2008 and continuous gauged flow data are available to March 2013. The available data are shown on Illustration 3.1.

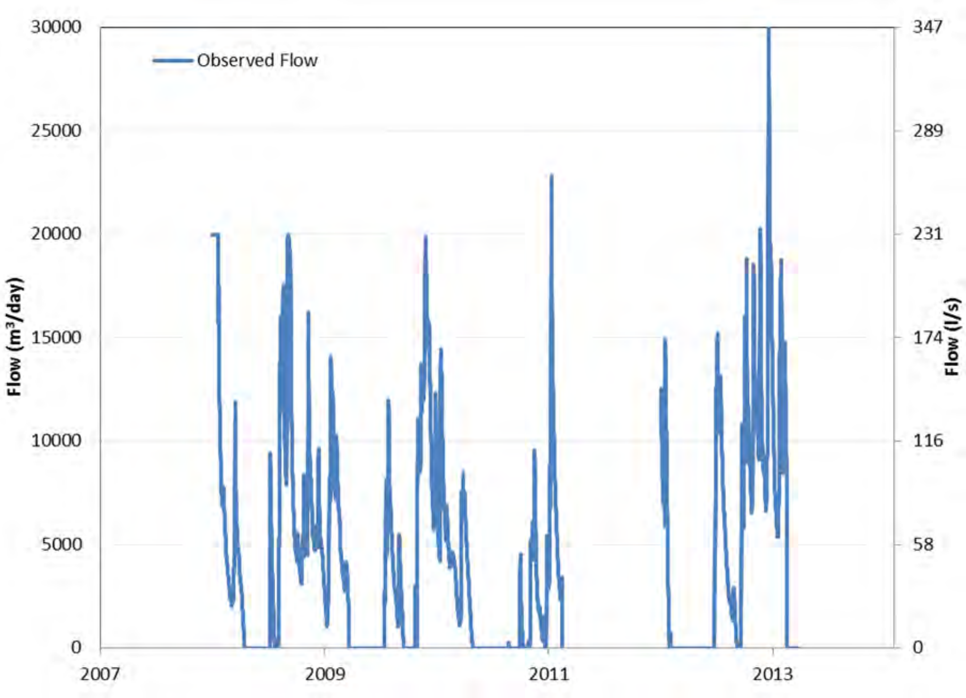


Illustration 3.1 Observed flow at Burrows Well

3.1.3 Pumping data

Cornelly Quarry is dewatered by pumping from a sump in the quarry floor to a settlement lagoon. In the past water has been pumped to Pant Mawr (and occasionally to Stormy Down), but currently water is pumped to Grove Quarry where water re infiltrates into the Carboniferous Limestone aquifer by seepage through the floor and sides of the flooded quarry.

Pumping data are available from June 2001 (Appendix N of Appendix 7.1), although the continuity and quality of the pumping records varies. Average pumping rates are summarised for different periods in Table 3.4 below.

Table 3.4 Average pumping rates at Cornelly quarry

Period	Sump	Offsite[1]	Comment
20 Jun 01 to 1 June 04	4873	1980	1202 m^3/d to Pant Mawr and 778 m^3/d to Grove
1 June 04 to 1 Oct 06	3382	1245	All to Grove from June 2004 to October 2006
1 Oct 06 and 5 Aug 08	-	2281	Assuming meter continued to run throughout
5 Aug 08 to 2 Jun 11	3735	2232	Since new meters installed
20 June 11 to 25 Mar 12	2969	2041	Since start of monitoring

[1] offsite excludes any re-circulation in the quarry itself

A complete record of inflow to Cornelly quarry has been reconstructed from the available data for the calibration period and is shown on Illustration 3.2 below. Note that the red line on this figure shows the average pumping rates for the periods where the quality of the monitoring data is considered to be reliable. Prior to available records (2001), estimates of the pumping rates have been made based on the available summary of dewatering activities at the quarry (Appendix N of Appendix 7.1). Net discharges to the lagoon and discharges offsite have also been calculated as part of the calibration process and are shown on

Illustration 3.3. Net discharges form explicit timeseries and are used as model input in respective model zones as discussed in Section 2.4.

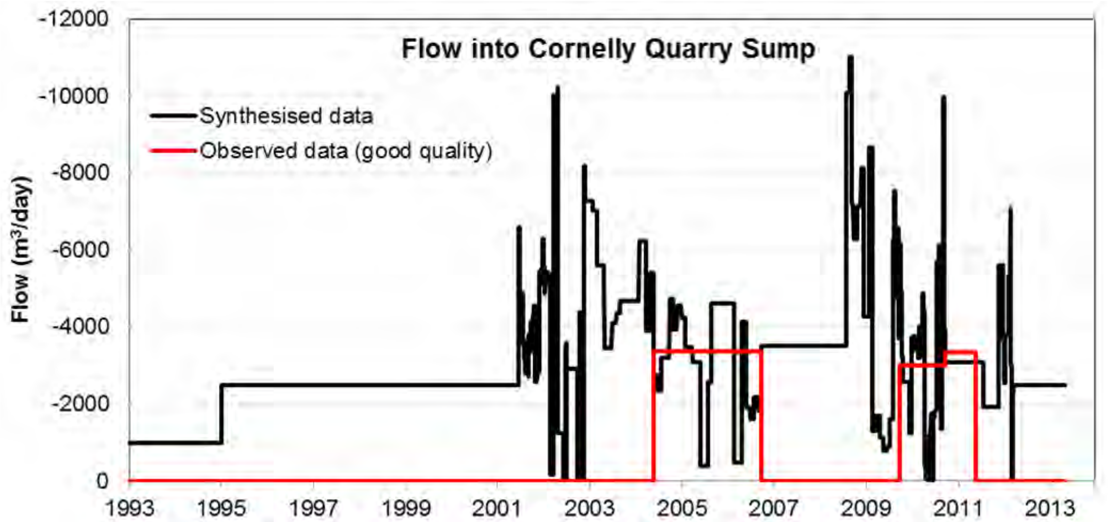


Illustration 3.2 Cornelly sump discharges used in model calibration

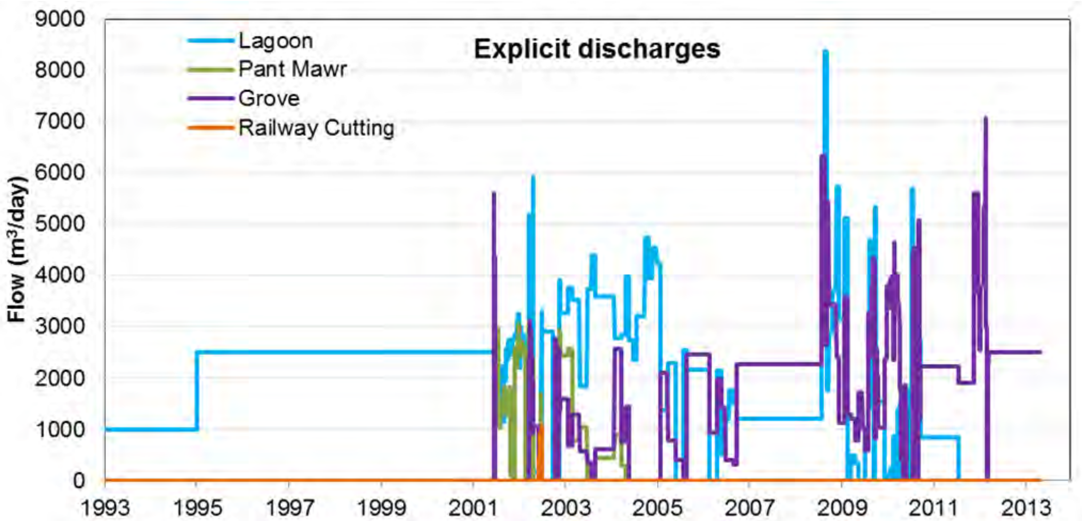


Illustration 3.3 Explicit discharges used in model calibration

Calibration of the inflows into Cornelly quarry is undertaken by using a history of development depths (see Illustration 3.4). Sump inflows are calculated from the development depths (Section 2.6) and compared to the observed (and synthesised) pumping rates from Cornelly sump. Clearly, data at different stages are more reliable than others, both due to uncertainty in the specified development depths and the reliability of the historical pumping data. Those data considered to be the more reliable data are shown on Illustration 3.2 and summarised in Table 3.5 below.

Table 3.5 Reliable pumping rates at Cornelly quarry

Period	Sump (m^3/day)
1 June 04 to 1 Oct 06	3382
5 Aug 08 to 2 Jun 11	3735

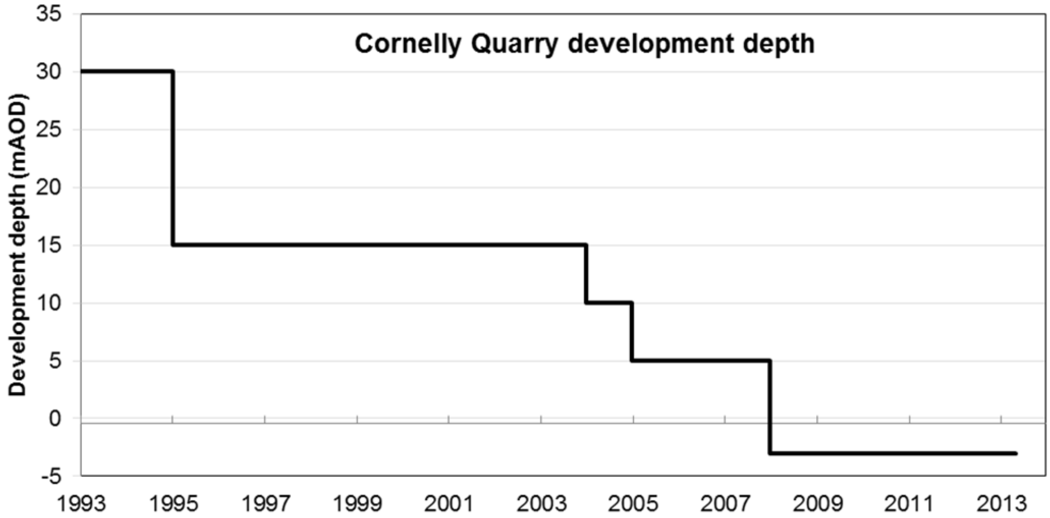


Illustration 3.4 Cornelly Quarry development depths

3.2 Initial Conditions

At the start of the simulation groundwater levels are set at an initial value using the average of field-measured head values (or interpolated values where no observation data are available for a given zone). These heads are not necessarily going to represent the groundwater system at equilibrium and response in the early time steps reflect the model under stress. The model requires some time to establish correct groundwater heads and flow (typically a period of one or two years from the start of the simulation is sufficient for the outputs to become reliable).

Initial heads used in the calibrated model in each zone are summarised in Table 3.6.

Table 3.6 Initial heads

Zone	Head	Zone	Head	Zone	Head	Zone	Head
1	42.0	16	24.0	31	16.0	46	10.2
2	34.0	17	24.0	32	12.0	47	10.8
3	60.0	18	24.0	33	5.0	48	9.7
4	60.0	19	22.0	34	20.0	49	9.0
5	60.0	20	64.0	35	22.0	50	8.4
6	57.0	21	64.0	36	8.0	51	8.6
7	57.0	22	50.0	37	6.0	52	8.3
8	39.0	23	23.0	38	9.0	53	10.4
9	34.0	24	15.0	39	12.0	54	10.0
10	60.0	25	10.0	40	10.0	55	9.0
11	56.0	26	5.0	41	6.0	56	10.3
12	58.0	27	17.0	42	12.9	57	9.9
13	31.0	28	9.5	43	8.5	-	-
14	31.0	29	61.0	44	6.1	-	-
15	24.0	30	13.8	45	8.3	-	-

3.3 Transmissivity

Groundwater flow between adjacent cells is a function of the transmissivity along the flow paths (a product of hydraulic conductivity and saturated thickness). Transmissivity is described by both geology considered to have constant transmissivities and those for which transmissivity varies as a function of the saturated thickness.

3.3.1 Fixed transmissivity

Solid geology

The final calibrated values of transmissivity for the solid geology are shown in Table 3.7. Values estimated during the development of the steady state model (ESI, 2003) are also shown for comparison.

Table 3.7 Calibrated transmissivity values for solid geology

Geology	Model transmissivity (m^2/day)		Zone
	Transient	Steady state	
Carboniferous limestone	see Table 3.9	n/a	1-33
Mercia Mudstone Marginal facies	700	1400	35,37-41
Penarth Group	20	20	34
Pant Mawr Sandstone	1	1	6,8,13,14, 18,26,27
Caswell Bay Mudstone	1	1	29
Undifferentiated Mercia Mudstone	800	20	34,36
Millstone Grit	0.1	n/a	37

The following observations were made during model calibration:

- Only one value of transmissivity per geology type was required to define the calibrated model.
- The Mercia Mudstone Marginal Facies typically exhibits higher transmissivity than the other formations (by an order of magnitude) and is within the expected range.
- The areas mapped as undifferentiated Mercia Mudstone is mapped as predominantly lower permeability mudstone[1], yet values similar to the marginal facies were required to achieve a good calibration:
    - o Higher transmissivity values were necessary to obtain sufficient spring flows and maintain low groundwater heads at connection leading to New Mills Farm spring.
    - o Transmissivity of other formations tended to dominate bulk transmissivity at other connections and results were less sensitive to the Mercia Mudstone value.
- Low transmissivity values for the Pant Mawr Sandstone were necessary to limit north-south connections around Grove and Pant Mawr and north of Cornelly quarry.
- An inferred low transmissivity connection between zones 36 and 37 due to the presence of Millstone Grit had only a minor effect on the overall calibration.

Superficial deposits

The final calibrated values of transmissivity for the superficial deposits at Merthyr Mawr and Kenfig are shown in Table 3.8. Note that the blown sand at Kenfig and Merthyr Mawr are modelled as unconfined; the hydraulic conductivity of the blown sand is constant, yet the transmissivity of the blown sand varies with the depth of the simulated groundwater level.

[1] Drilling of Boreholes O and R near New Mill farm springs showed that the geology in this area comprised marginal facies rather than the mudstone as mapped. This provides some justification for high transmissivities used in the model in this area.

Table 3.8 Calibrated transmissivity values for superficial deposits

Geology	Model transmissivity (m^2/day)		Zone
	Transient	Steady state	
Kenfig			
The blown sand	109-163	n/a	54-57
Sands and Gravels	50	90	46-52
Alluvium	0.5	n/a	53
Till+ Sands and Gravels [1]	0.05	n/a	49-52
Merthyr Mawr			
The blown sand	108-270	n/a	42-45

1 bulk transmissivity

The following observations were made during model calibration:

- The calibrated values for the hydraulic conductivity of the blown sand at Kenfig and Merthyr Mawr are 15 m/day and 20 m/day respectively. Jones (1993) carried out numerous falling head tests and estimated a mean hydraulic conductivity of around 9 m/day. Scoping calculations based on observed hydraulic gradients and estimated recharge suggest that the value could be up to 25 m/day (Appendix G of Appendix 7.1).
- The glaciofluvial sands and gravels at Kenfig represent a relatively permeable horizon, yet a limited connection to the sea via the till is required to support the observed groundwater levels.
- The lateral connection between the glaciofluvial deposits and the sea via the till represents a boundary connection and a bulk transmissivity. The equivalent transmissivity of the till would be approximately 0.0005-0.0009 m^2/day. Assuming a thickness of 8 m this is approximately an order of magnitude greater than the vertical till hydraulic conductivity (see Section 3.3.4).
- A relatively permeable lateral connection (via alluvium) is required from Kenfig Pool (Zone 53) to adjacent cells to achieve model calibration. Assuming a thickness of 5 m this gives a hydraulic conductivity of approximately 0.01 m/day, which is two orders of magnitude greater than the vertical hydraulic conductivity of the alluvium (see Section 3.3.4).

3.3.2 Depth dependent transmissivity

Flow into Cornelly quarry is principally via diffuse flow from fractures and fissures. Detailed work on the distribution of palaeokarst features (Appendix H of Appendix 7.1) indicates that most of the active fissures are present above 60 mbgl, with the frequency of clay filled features increasing significantly with depth. Very few fissures are observed below 100 mbgl toward the base of the quarry. Evidence also suggests that there are no significant palaeokarst features that may enhance groundwater flow from the current base of the quarry to at least -75 mAOD.

A review of the groundwater level hydrographs within the Carboniferous Limestone also suggests that a general model of enhanced permeability is applicable in a zone immediately above and below the position of the current water table. Groundwater levels fall rapidly after winter recharge, but generally most boreholes show a lower level to which groundwater levels fall. This lower level is typically controlled by the elevation of a zone of enhanced permeability.

These observations suggest up to three hydraulic conductivity horizons within the Carboniferous Limestone; with the highest values representative of an uppermost, reactivated palaeokarst zone, the middle zone representing partial reactivation and the lower zone representing an area of no reactivation.

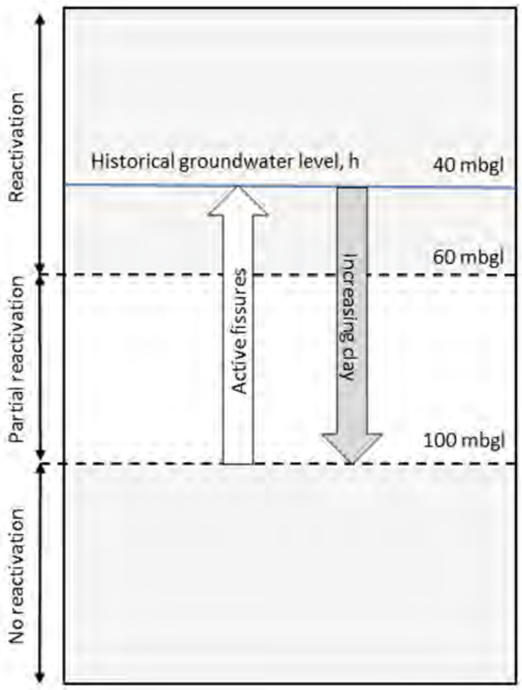


Illustration 3.5 .Palaeokarst features and VKD horizons at Cornelly quarry

Initial parameterisation of VKD was based on these three distinct hydraulic conductivity horizons in the Carboniferous Limestone. In summary, each layer elevation was defined as:

- top of layer 1, mean topographical elevation of each zone;
- top of layer 2, varies linearly with zone elevation;
- top of layer 3, top elevation of no reactivation, and;
- top of layer 4 (base of layer 3), the lower vertical limit of the model.

The top elevation of no reactivation was considered to be fixed at 0 mAOD based on the observations at Cornelly quarry. The lower bound to the model was set at -100 mAOD (at sufficient depth to consider future developments within the quarry). The base of the reactivated palaeokarst horizon (top of layer 2, $z_{j,L2}$) was considered to vary linearly with surface elevation according to:

$$z_{j,L2} = z_j.\frac{z_{max} - d_{max}}{z_{max}}$$

where z_j is the mean topographical elevation of each zone (m),

z_{max} is the maximum topographical elevation in the model area (m),

d_{max} is the depth to L2 at the maximum topographical elevation (m),

The figure below shows the resulting vertical extent of the horizons in each zone. The range of observed groundwater level variation is also shown and illustrates that the uppermost reactivated karst horizon is active at higher groundwater levels for this linear approximation.

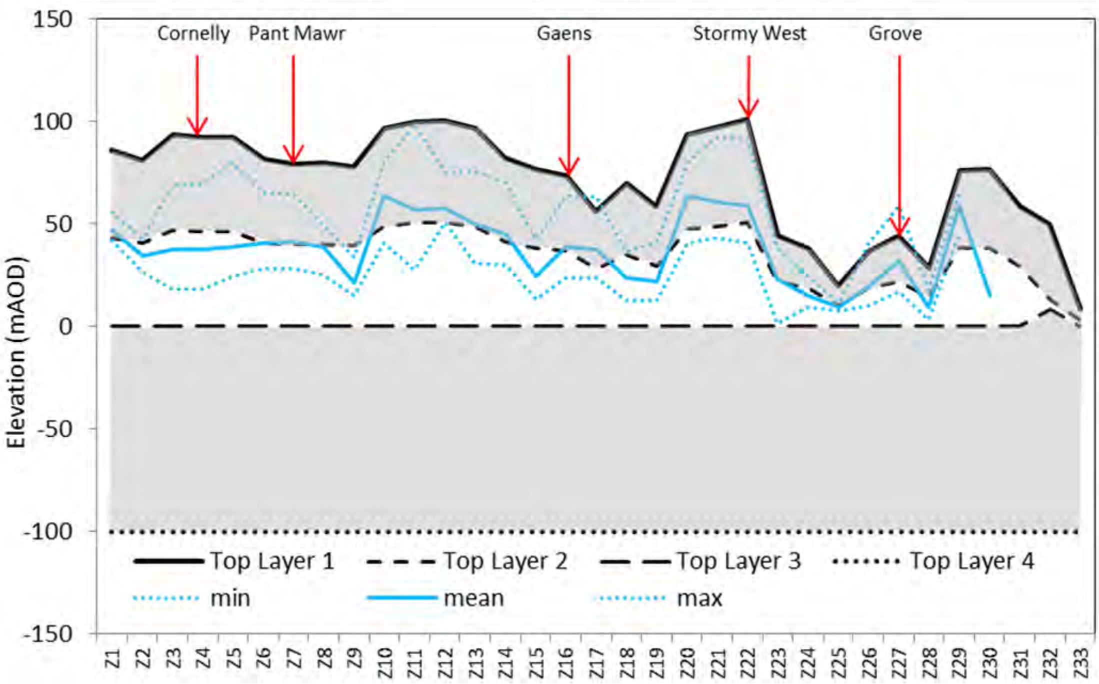


Illustration 3.6 VKD horizons by zone

In general, the initial parameterisation of layer elevations has remained unchanged during calibration. One exception is Zone 32 (associated with the outflow at Burrows well). The base of the zone of increased hydraulic conductivity at this location represents a physical discharge point from the aquifer.

A summary of the calibrated depth dependent hydraulic conductivity distribution at all Carboniferous Limestone zones is shown in Table 3.9. In order to limit issues of over parameterisation an attempt was made to restrict the number of distinct hydraulic conductivity values used. The vertical hydraulic conductivity profiles can be categorised in to broadly four categories (as shown on Table 3.9).

Table 3.9 Calibrated depth dependent hydraulic conductivity

		Layer Geometry (mAOD)				Hydraulic Conductivity (m/day)			
Id	ZONE	Top Layer 1	Top Layer 2	Top Layer 3	Top Layer 4	Layer 1	Layer 2	Layer 3	Category
Lagoon	Z1	86.1	43	0	-100	4.00	0.75	0.05	2
	Z2	81.3	41	0	-100	3.00	0.20	0.03	2
	Z3	93.6	47	0	-100	3.00	0.20	0.03	2
Cornelly Quarry	Z4	92.1	46	0	-100	4.00	0.75	0.05	2
	Z5	92.1	46	0	-100	0.01	0.01	0.01	1
	Z6	81.4	41	0	-100	3.00	0.20	0.03	2
Pant Mawr	Z7	79.0	40	0	-100	3.00	0.20	0.03	2
	Z8	80.1	40	0	-100	3.00	0.20	0.03	2
	Z9	77.8	39	0	-100	3.00	0.20	0.03	2
	Z10	96.8	49	0	-100	3.00	0.20	0.03	2
	Z11	100.1	51	0	-100	3.00	0.20	0.03	2
Stormy Down Quarry	Z12	100.5	51	0	-100	0.10	0.10	0.10	1
	Z13	96.7	49	0	-100	4.0	4.0	0.05	3
	Z14	82.1	41	0	-100	3.0	0.2	0.03	2
	Z15	76.5	39	0	-100	4.0	4.0	0.05	3
Gaens	Z16	73.9	37	0	-100	4.0	4.0	0.05	3
	Z17	55.9	28	0	-100	4.0	4.0	0.05	3
	Z18	70.0	35	0	-100	4.0	4.0	0.05	3
	Z19	58.3	29	0	-100	3.00	0.20	0.03	2
	Z20	93.8	47	0	-100	3.00	0.20	0.03	2
	Z21	97.1	49	0	-100	3.00	0.20	0.03	2
Stormy West Quarry	Z22	101.0	51	0	-100	3.00	0.20	0.03	2
	Z23	44.1	22	0	-100	5.0	5.0	0.05	3
EA South Cornelly	Z24	37.7	19	0	-100	4.0	4.0	0.05	3
	Z25	20.1	10	0	-100	4.0	4.0	0.05	3
	Z26	37.0	19	0	-100	5.0	5.0	0.05	3
Grove	Z27	44.0	22	0	-100	5.0	5.0	0.05	3
	Z28	28.8	15	0	-100	5.0	5.0	0.05	3
Itusca	Z29	76.0	38	0	-100	1.0	1.0	0.01	1
Plateau -	Z30	76.5	39	0	-100	4.0	4.0	0.01	3
Plateau -	Z31	58.3	29	0	-100	4.0	4.0	0.01	3
Plateau -	Z32	50.0	13	8.0	-100	50.0	4.0	0.01	4
Burrows Well	Z33	8.5	3	0	-100	10.0	1.0	0.01	4

3.3.3 Resultant transmissivity values

Transmissivity values between adjacent zones are calculated from the transmissivity of each geology type between adjacent cell nodal points from their harmonic mean (as detailed in Section 2.5). The transmissivity for each connection is shown on Figure 3.2. Minimum, maximum and mean transmissivity values are shown where transmissivity varies as function of the groundwater level over time.

This figure shows a large number of different transmissivities being applied between the zones both spatially and with time (derived from the smaller number of values of transmissivity within the zones).

3.3.4 Vertical hydraulic conductivity

Vertical component of flow have to be considered at Kenfig Dunes and Merthyr Mawr. Table 3.10 shows the calibrated vertical hydraulic conductivity values. The values are consistent with the range of values expected for lithologies of these types.

Table 3.10 Calibrated hydraulic conductivity values

Lithology	K_v (m/d)	Zones
Carboniferous Limestone	0.5	25,33
MMMF	1.0	37,38,39
Kenfig		
The Blown Sand	10	54-57
Sands and Gravels	0.1	46-52
Alluvium	1×10^{-4}	53
Lacustrine	5×10^{-5}	53,55-57
Till[1]	1×10^{-5}	47-52
Merthyr Mawr		
The blown sand	10	42-45
Till[1]	1×10^{-4}	42-45

1 vertical connection, not explicit model zone

In previous supplementary calculations (WynThomasGordonLewis, 2004) a water balance for the groundwater system at Kenfig pool estimated the vertical hydraulic conductivity of lacustrine deposits to be 10^{-4} m/day.

3.4 Storage

Storage parameters were assigned based on geology type (and other conceptual controls, such as confined and unconfined conditions) and further refined throughout the calibration process. The final calibrated storage values are shown on Figure 3.3 and summarised in Table 3.11 below. Calibrated values were typically well within expected ranges for these types of lithologies (see discussion below).

Table 3.11 Calibrated storage values

Zone	Storage	Zone	Storage	Zone	Storage	Zone	Storage
1	1.00×10^{-1}	16	1.23×10^{-2}	31	2.22×10^{-2}	46	2.00×10^{-1}
2	1.23×10^{-2}	17	1.23×10^{-2}	32	2.00×10^{-3}	47	2.00×10^{-1}
3	2.50×10^{-3}	18	1.23×10^{-2}	33	2.00×10^{-4}	48	5.00×10^{-4}
4	2.50×10^{-3}	19	1.23×10^{-2}	34	5.00×10^{-2}	49	5.00×10^{-4}
5	1.23×10^{-2}	20	2.50×10^{-3}	35	1.00×10^{-2}	50	5.00×10^{-4}
6	1.23×10^{-2}	21	1.23×10^{-2}	36	5.00×10^{-2}	51	5.00×10^{-4}
7	1.00×10^{-1}	22	1.23×10^{-2}	37	6.00×10^{-3}	52	5.00×10^{-4}
8	1.23×10^{-2}	23	2.50×10^{-3}	38	3.00×10^{-3}	53	1.00×10^{0}
9	1.23×10^{-2}	24	2.22×10^{-2}	39	5.00×10^{-2}	54	4.00×10^{-1}
10	2.50×10^{-3}	25	2.22×10^{-2}	40	2.00×10^{-2}	55	4.00×10^{-1}
11	2.50×10^{-3}	26	1.23×10^{-2}	41	5.00×10^{-2}	56	4.00×10^{-1}
12	1.00×10^{-1}	27	5.00×10^{-2}	42	3.00×10^{-1}	57	4.00×10^{-1}
13	1.23×10^{-2}	28	2.22×10^{-2}	43	3.00×10^{-1}	-	
14	1.23×10^{-2}	29	1.00×10^{-2}	44	2.50×10^{-1}	-	
15	1.23×10^{-2}	30	2.22×10^{-2}	45	2.50×10^{-1}	-	

Values of storage assigned to the unconfined Carboniferous Limestone varied between 2.0×10^{-3} 5.0×10^{-2}. Higher values of storage (0.1) were assigned to some Carboniferous Limestone zones (Zones 1, 7, 12) to account for additional storage in lagoons and pools. The lowest value of storage (2.0×10^{-4}) was assigned to the confined Carboniferous Limestone at Merthyr Mawr (Zone 33). Note that parameterisation of the confined Carboniferous Limestone at Merthyr Mawr causes some numerical issues, with lower values of storage causing model instability.

Storage values between 0.25 and 0.3 were used for the blown sand at Merthyr Mawr, whereas values of 0.4 were needed to represent the observed groundwater level fluctuations at Kenfig. The value at Kenfig represents the upper value of the expected range although it is not clear how much additional storage from the dune slacks may contribute to this figure.

3.5 Additional Storage

Three additional storage areas have been implemented in the calibrated model (summarised below in Table 3.12). Zone 1 represents the settlement lagoon associated with Cornelly quarry. Zone 42 and Zone 43 represent the pools and dune slacks to the south of the spring discharge at Burrows Well. Fractional areas (with respect to the zone area) and base elevations have been estimated from available survey data and groundwater levels. All bodies represent open water and a storage value of 1.0 is used.

Table 3.12 Additional storage areas

Zone	Elevation (mAOD)	Fractional area (-)	Storage (-)	Description
1	42	0.1	1.0	Lagoon
42	12	0.03	1.0	Upper Pool
43	8	0.07	1.0	Lower Pool

These additional storage areas were included where the existence of substantial surface water bodies are clearly apparent and may influence model results. Features such as dune slacks and other smaller surface water features are not explicitly represented in the model.

3.6 Boundary Conditions

3.6.1 Discharge

There are a number of licensed abstractions in the model area (Table 3.13). Discrete abstractions have been used to represent these pumping at their daily licensed values.

Table 3.13 Abstractions in the model area

Licence	X	Y	Description	Abs. (m^3/day)	Zone
21/58/51/0030	282240	180790	General Agriculture	14.6	23
21/58/33/0007	285640	178830	General Agriculture	22.7	29
21/58/51/0028	279850	183200	Commercial and Public Services	415.9	36
21/58/51/0010	279790	183480	Commercial and Public Services	1636.6	36
21/58/33/0004	282230	178120	General Agriculture	9.3	41
21/58/33/0006	282020	178550	General Agriculture	6.8	41

3.6.2 Springs

Spring boundary conditions are set at the observed spring elevations. The main springs that need to be simulated are those at New Mill Farm and Burrows Well, which are at elevations 7.9 mAOD and 13.0 mAOD respectively. Water discharging at Burrows Well is controlled via 'boundary re-direction' detailed in Section 3.6.4 below.

3.6.3 Drains

Kenfig Pool (Zone 53) has an average water level of around 10.3 mAOD which fluctuates by ±0.3 m in response to climatic conditions (Appendix K of Appendix 7.1). The pool is reported to be around 3.0 m deep and at high water levels overflows to the south west (Zone 55).

Kenfig pool is simulated as a distinct zone with a storage of 1.0 and an initial head of 10.4 mAOD. The base of the pool is effectively undefined, but a drain boundary condition is applied at 10.5 mAOD. Water overtopping this elevation is controlled via 'boundary re-direction' detailed in Section 3.6.4 below.

3.6.4 Boundary re-direction

Table 3.14 summarises the boundary re-direction implemented in the calibrated model.

Table 3.14 Boundary re-direction

Zone		Re-direction				Boundary
From	To	Area (m^2)	Fraction	Logic	Volume (m^3)	
32	42	163480	-	1	70654	Spring
32	43	371755	-	1	1000000	Spring
53	55	971716	1.0	0	0.0	Drain

Burrows Well

Redirection from Burrows Well (Zone 32) uses a logical process that best describes the conceptual understanding at this location. The logical process works in combination with the additional storage assigned to the upper pool (Zone 42) and lower pool (Zone 43) summarised in Table 3.12.

Within any given timestep the model accounts for the amount of storage in the upper pool and the quantity of spring flow available for re-direction. If the additional storage in Zone 42 exceeds 70654 m^3, any remaining spring flow is redirected to additional storage in Zone 43.

The maximum storage volume assigned to zone 32 is calculated from:

$$V_j = (S_{a,j} f_j A_j + S_j (1 - f_j) A_j).\, d_j$$

where V_j is additional storage volume (m^3),

$S_{a,j}$ and S_j are the additional and normal zone storage values respectively (-),

A_j is the zone area (m^2),

f_j is the fractional area of additional storage (-),

d_j is the additional storage depth (m),

The area of the upper pool (Zone42) is estimated to be 5262 m^2. Assuming the depth of the pool is approximately 1.4m this gives a total additional storage volume of water 70654 m^3. Pool volume in Zone 43 set to a sufficiently high value such to ensure all remaining spring flow can be re-directed and the water balance within the model is conserved.

Kenfig Pool

Redirection from Kenfig Pool (Zone 53) assumes that all water overtopping is discharged to Zone 55. .

3.7 Assessment of Calibration

In the following sections, the results of groundwater model are presented in terms of simulated groundwater heads, spring flows and water balances, and compared with observed data, where available.

3.7.1 Groundwater levels

A comparison between simulated and observed groundwater levels across the model area, are shown in Illustration 3.7-Illustration 3.11 (grouped spatially within model areas). These figures present the comparison of simulated groundwater heads at the nodal point of each cell and the corresponding observed data.

General acceptance criteria for a suitable representation of the simulations groundwater level timeseries are as follows:

1. A good representation of seasonal and long term trends should be achieved.
2. The ability of the model to replicate absolute observed groundwater levels is somewhat subjective (given that observation boreholes are not always located near to the cell node point), but groundwater levels simulated by the model are defined as good when within 5 m of the observed heads.

These criteria have been used to assess the simulation of groundwater level at the target locations listed in Table 3.1. ‘Average’ groundwater level residuals (observed-simulated) have been calculated for each target location. The time period used to calculate the ‘average’ groundwater level is defined by the availability of observation data at each location.

Table 3.15 Groundwater residuals

Zone	BH	mean error	absolute mean error	standard deviation	Zone	BH	mean error	absolute mean error	standard deviation
1	TQ3	6.9	7.8	4.2	29	I_TUSCA	-0.4	4.6	5.7
2	ESP2	0.5	2.7	3.7	30	T[1]	-	-	-
3	TM6	-6.1	8.7	10.8	33	MM1	0.5	1.2	1.4
4	TM6	-12.4	12.7	10.5	35	P	-6.2	6.1	2.5
5	TM4	-10.8	10.8	6.6	36	O-A	0.8	0.8	0.5
8	RW107	-1.6	4.3	5.5	38	A-A	-3.5	3.6	2.0
9	RWC105	0.4	3.7	4.4	40	B-A	0.2	1.5	2.1
10	G	-9.8	10.0	6.6	41	21	2.0	2.1	1.2
11	T95/01	-5.4	8.7	9.6	42	L	1.8	1.8	0.5
12	T95/04	1.1	6.4	7.5	43	D7	1.7	1.9	1.6
14	Q	-0.2	5.9	7.2	44	L	-5.1	5.1	0.4
15	E	2.1	4.6	5.2	45	D4	-0.4	0.5	0.4
18	RWC105	1.9	6.0	6.5	46	N-C	1.2	1.4	1.1
20	G	-2.9	5.9	6.9	47	A-B	-2.0	2.1	1.6
23	17B	-2.3	5.1	6.0	48	KP	-0.5	0.6	0.5
24	EASC	-1.4	2.6	3.3	50	K1A	-0.3	0.6	0.7
25	N-A	1.0	1.2	1.1	53	KP	0.2	0.3	0.2
26	RWC100	-0.3	2.9	3.6	55	K1B	-1.1	1.2	0.6
27	RWC100	4.3	5.2	4.2	56	CC5	-0.1	0.4	0.5
28	40	4.6	4.7	2.7					

1 observed data after end of simulation period

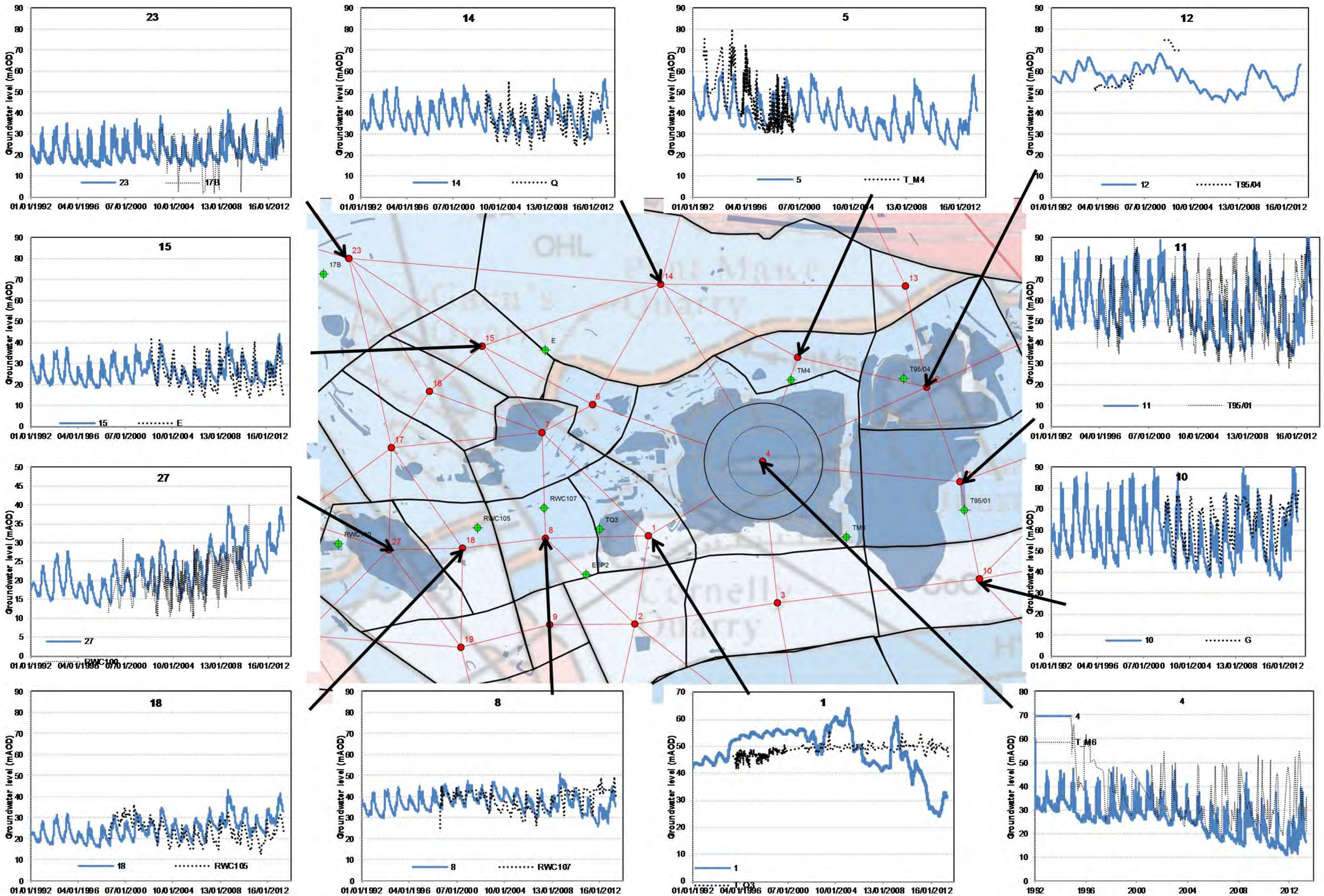


Illustration 3.7 Simulated and observed groundwater levels - Cornelly

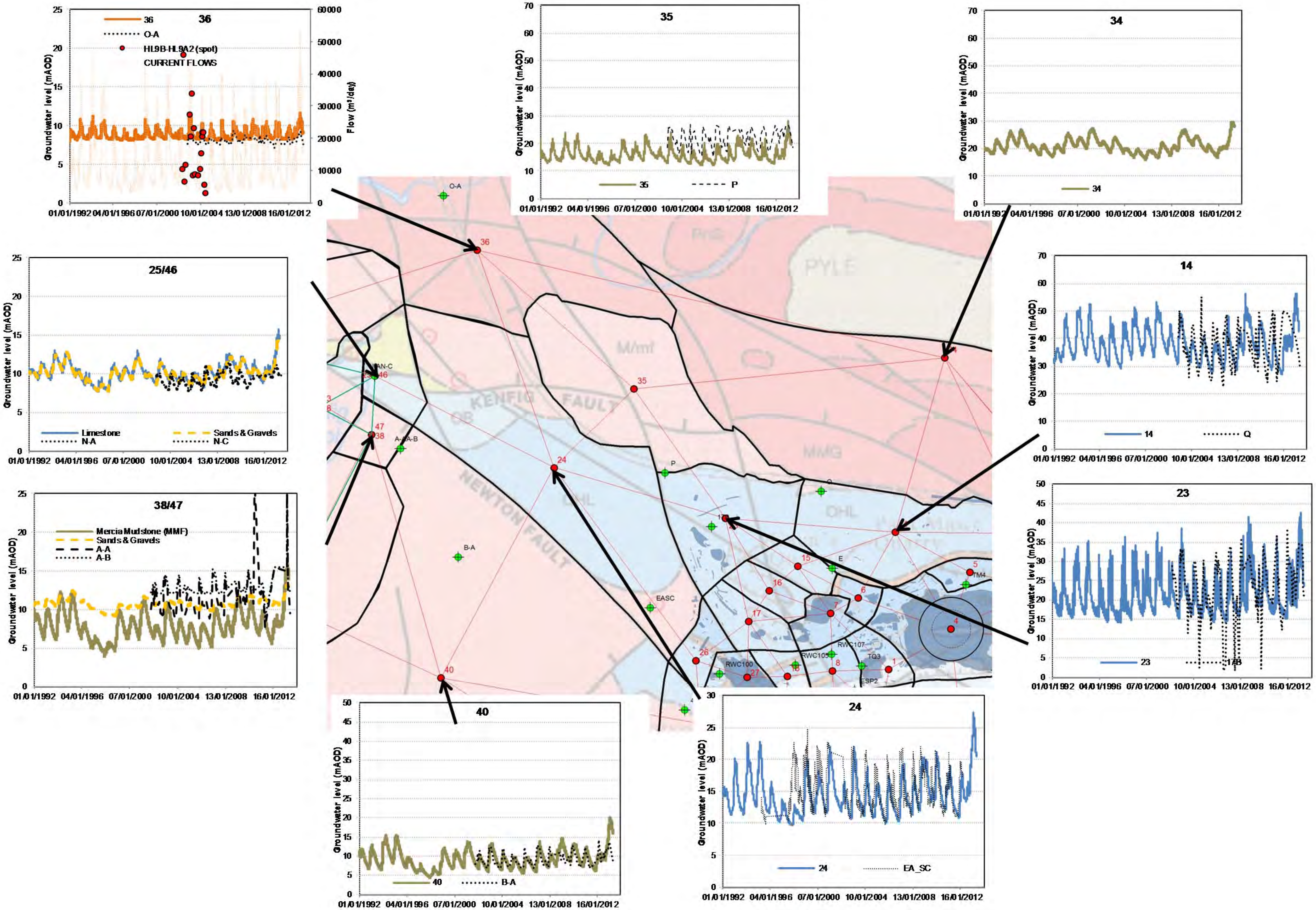


Illustration 3.8 Simulated and observed groundwater levels – N Cornelly

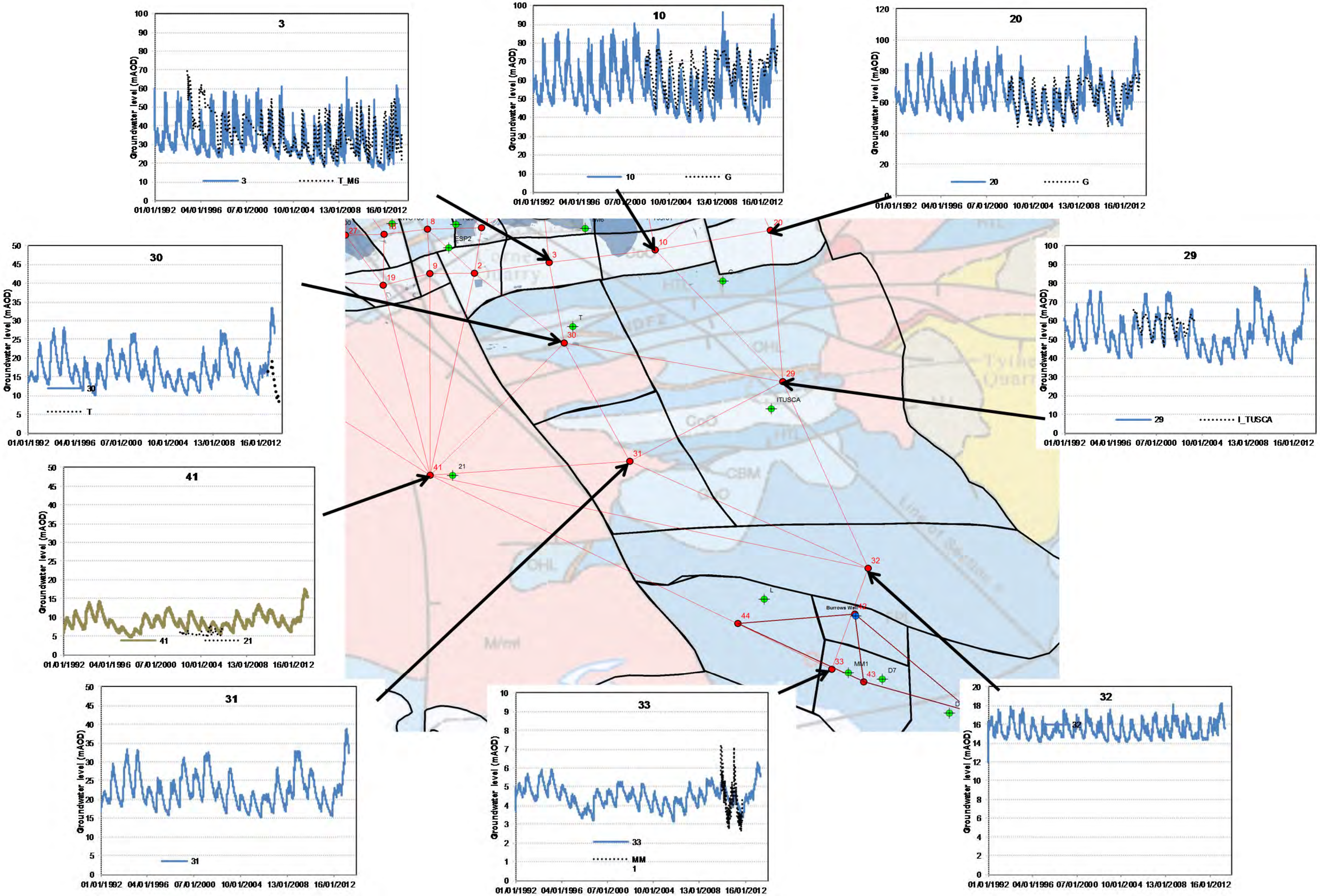


Illustration 3.9 Simulated and observed groundwater levels – Plateau

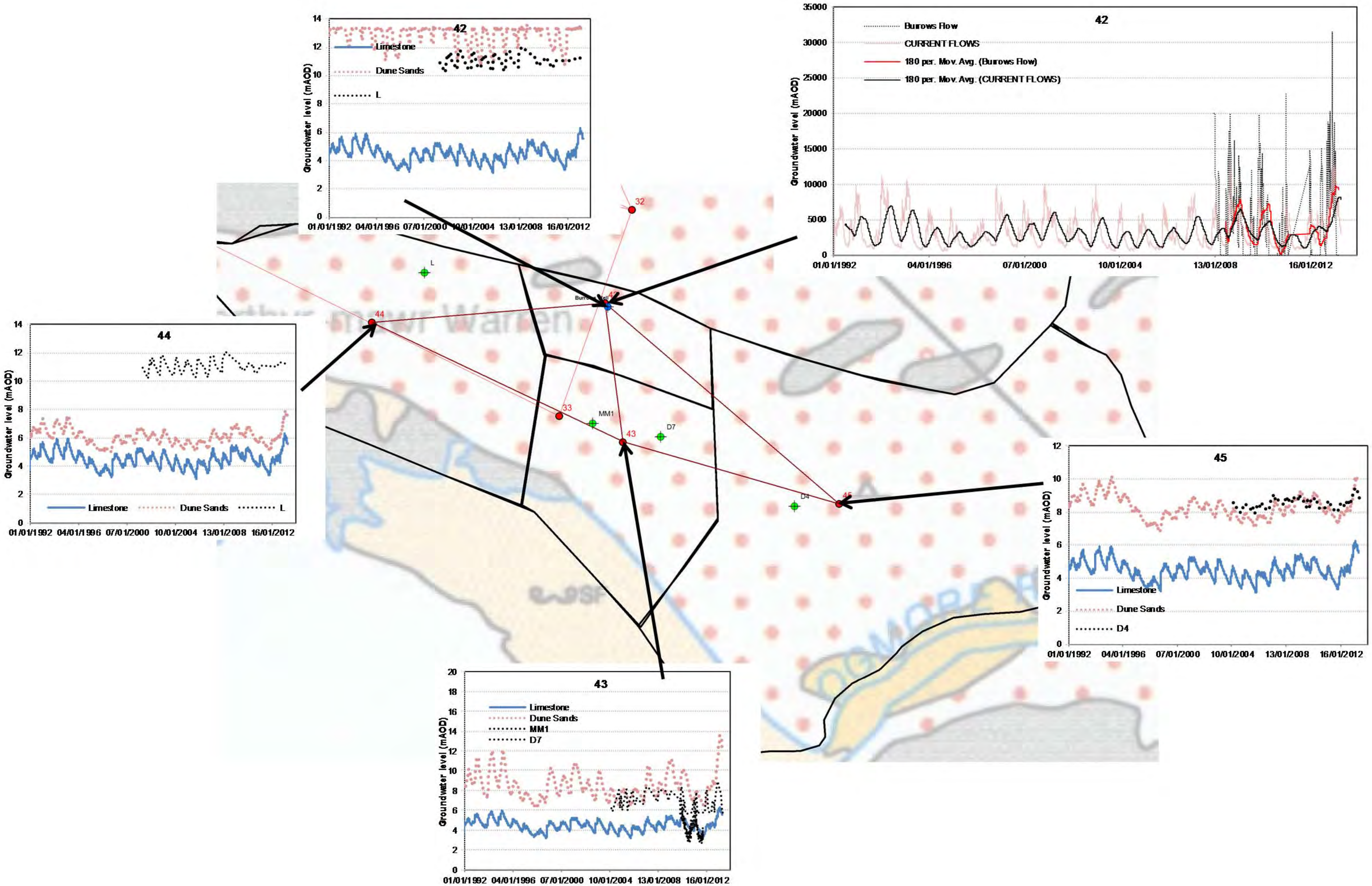


Illustration 3.10 Simulated and observed groundwater levels – Merthyr Mawr

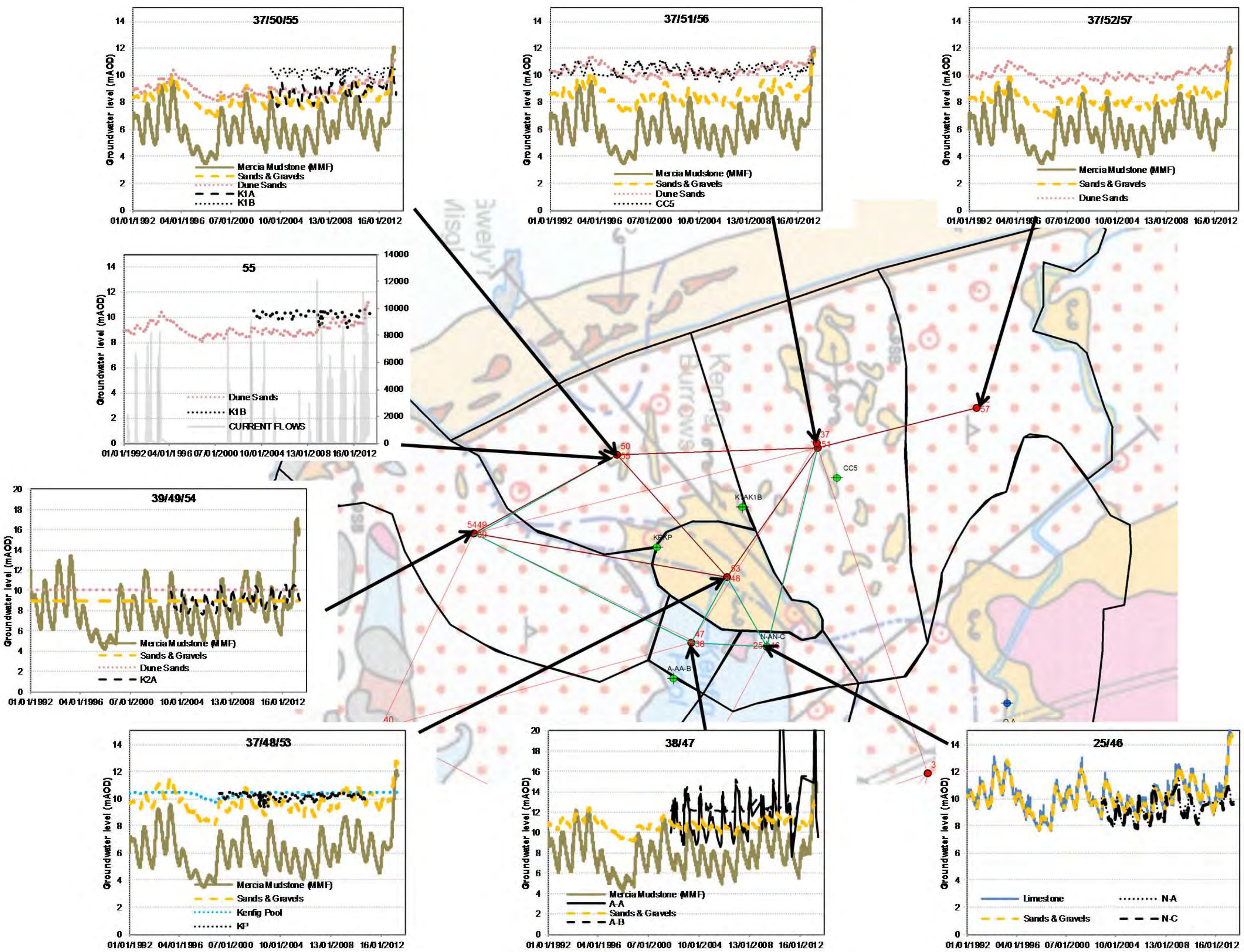


Illustration 3.11 Simulated and observed groundwater levels – Kenfig (North to right)

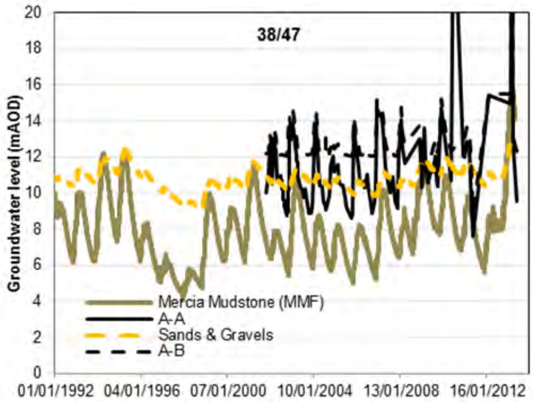
It can be seen that the model simulates the seasonal and long term groundwater level trends well. Average deviations between modelled and target heads in the superficial deposits is typically less than 2.0 m. The deviations in the simulated heads in the Carboniferous Limestone are typically 5.0 m or less. The average simulated groundwater levels are well within the total observed range and the calibration is considered acceptable. There are some obvious disparities, for example in Zone 1, where the observed groundwater level is that of the settlement lagoon, and is in all likelihood a perched groundwater level.

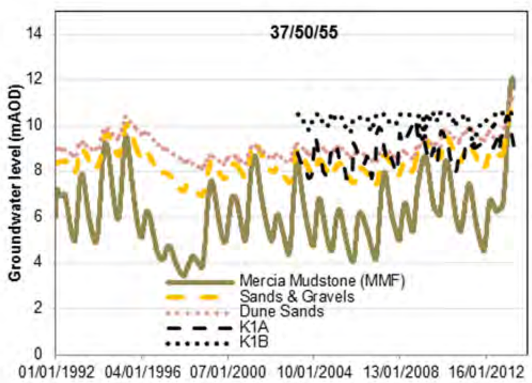
The greatest variations to the observed heads (>5.0 m) are in the vicinity of the Cornelly Quarry (Zones 3, 4, 5, 10, 11). At these locations the observation boreholes are typically at some distance from the modelled groundwater level. Given the relatively coarse zonal representation within the groundwater model and the large variation in the range in groundwater levels these absolute discrepancies are not unexpected and the observed trend is of greater significance in these locations.

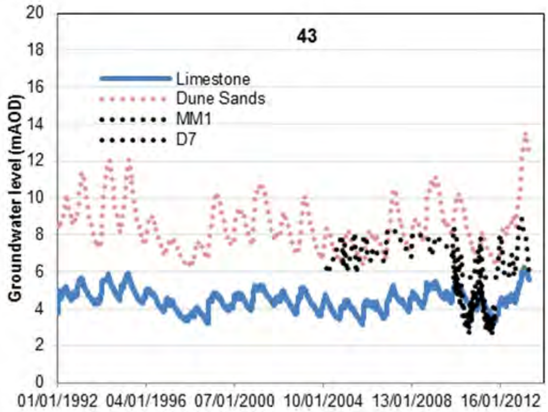
The ability of the model to simulate vertical gradients between the underlying geology and the dune systems at Kenfig and Merthyr Mawr can also be assessed. Table 3.16. compares the long term average simulated and observed groundwater gradients at multi-level monitoring locations (or those monitoring locations in the solid geology and superficial deposits located sufficiently close to allow an assessment).

Table 3.16 Vertical gradients

	Upper	Lower	i(obs)	i(mod)
Kenfig	A-B (GSG)	A-A (MMF)	0.16	0.28
Kenfig	K1B(DS)	K1A(GSG)	0.18	0.08
Merthyr Mawr	D7(DS)	MM1(CL)	0.40	0.60







The model simulates the long term groundwater level trends reasonably well, although the variation in the groundwater level in the underlying Carboniferous Limestone at Merthyr Mawr is underestimated due to model stability issues (Section 3.4). Discrepancies in the magnitudes of the vertical hydraulic gradient largely correspond with the distance between the observed and modelled groundwater levels, and their relative positions along each flow path.

3.7.2 Springs

Spring flows have been simulated by specifying an appropriate fixed head within the spring cell and deriving the flow from the model calculations. A comparison to available data at the gauging stations provides an indication of the ability of the model to reproduce observed flows.

<u>New Mills Farm Springs</u>

Modelled and observed flows at New Mill Farm Springs are shown on Illustration 3.12 and summarised in Table 3.17. Table 3.17 shows the long term average (LTA) observed and simulated flows over the period for which observations are available. The LTA at the New Mill Farm Springs are also shown demonstrating the variation under different recharge conditions.

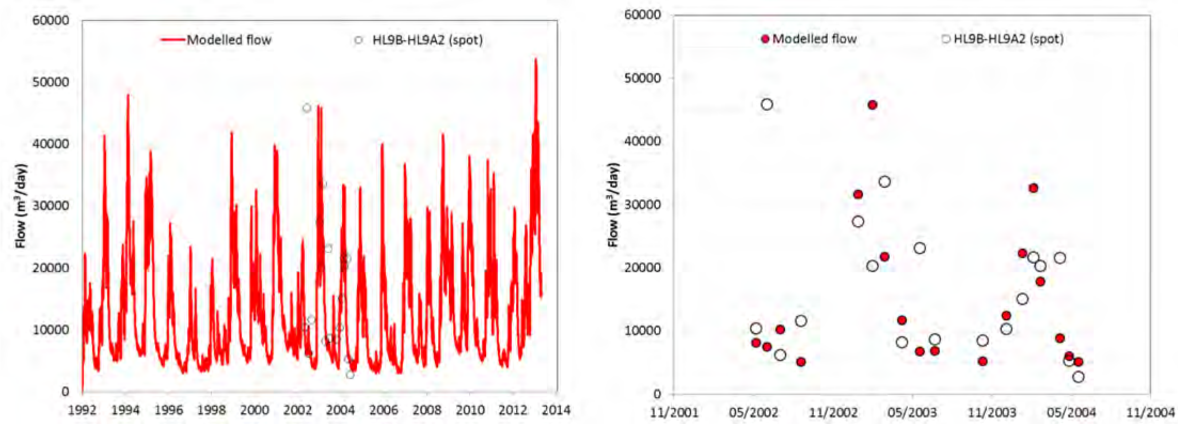


Illustration 3.12 New Mill Farm springs

Table 3.17 Observed and simulated flows at New Mill Farm Springs

Observed Flow (m^3/day)	Simulated Flow (m^3/day)	Difference[1] (%)	Comments
16735	14786	-11.7	Calibrated model
16735	17372	3.8	+15% recharge
16735	12379	-26.0	-15% recharge

1 relative to observed

Modelled flows are within 12% of the observed. Differences are relatively small given the overall uncertainty in the recharge rate (+/-15%) in addition to the relatively small number of spot gauging observations against which to compare model results. Simulated flow compares favourably with observed and together with simulated groundwater levels results are considered to provide an adequate representation of flows using current recharge estimates with the calibrated transmissivities of the various formations.

<u>Burrows Well</u>

Modelled and observed flows at Burrows Well are shown on

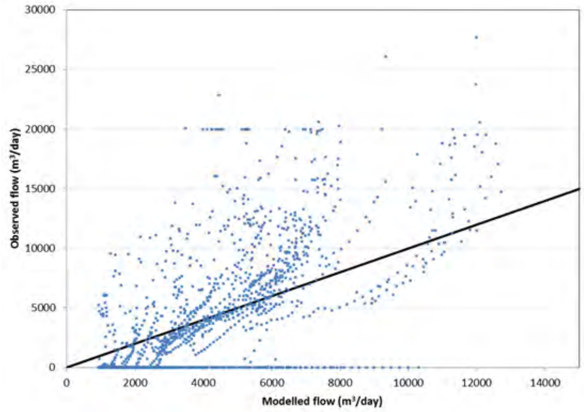
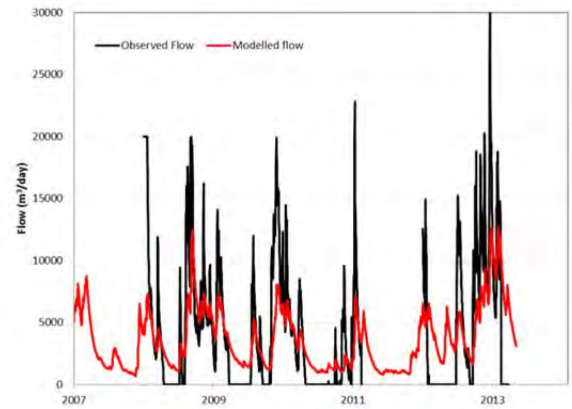
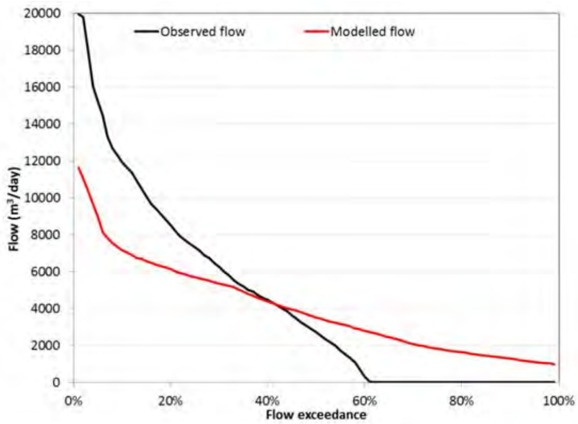


Illustration 3.13 as flow hydrographs and as a flow duration curve (flow hydrographs provide an indication of the accuracy of the model in simulating both magnitude and timing of flows; while flow duration curves assess the ability to reproduce flows under different flow conditions). Modelled versus observed flows are also shown on this figure.





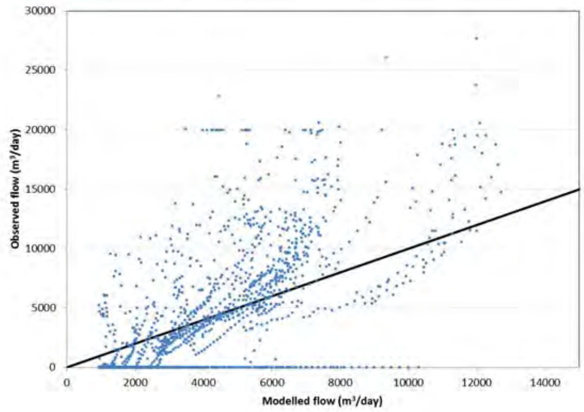


Illustration 3.13 Burrows well

Table 3.8 shows the average observed and simulated flows over the period for which observations are available. The LTA at the Burrows Well are also shown demonstrating the variation under different recharge conditions. Table 3.19 summarise key calibration statistics for average flows and Q95 flows respectively. •

Table 3.18 Observed and simulated LTA flows at Burrows Well

Observed Flow (m^3/day)	Simulated Flow (m^3/day)	Difference[1] (%)	Comments
4418	4047	-8.4	Calibrated model
4418	4685	6.0	+15% recharge
4418	3424	-22.5	-15% recharge

1 relative to observed

Table 3.19 Observed and simulated flows at Burrows Well

%	Observed (m^3/day)	Simulated	Difference
5	15,253	9,001	-41%
15	10,515	6,696	-35%
25	7,322	5,693	-22%
50	2,731	3,530	29%
75	0	1,831	-
85	0	1,444	-
95	0	1,122	-

LTA modelled flows are within 8.4% of the observed. These differences are not considered significant given the overall uncertainty in the recharge rate (+/-15%) and the subsequent variation in simulated flows. However, although the LTA flows are simulated reasonably well and the overall seasonal pattern of flows is also simulated effectively, the flow duration curve and modelled versus observed flows indicate that the model does not simulate the ‘flashy’ nature of Burrows Well. Simulated flows exceed observed at low flows, whereas flows are underestimated at peak flows.

Intermittent flow from the underlying Carboniferous Limestone and the discharges at Burrows Well involve the interaction between Zones 32-33 (Carboniferous Limestone), the Burrows well spring boundary, and re-direction to Zones 42-43 (Blown Sands). When groundwater levels in Zone 32 are sufficiently high, discharge occurs to Burrows Well by accessing the transmissivity above the spring elevation. Discharge to the Blown Sands from Burrows Well in turn interacts with the underlying Carboniferous Limestone in Zone 33. There is also a flow component between Zones 32 and 33 which accesses the transmissivity beneath the spring elevation, which influences groundwater levels at these locations. Difficulties in representing flows at Burrows Well largely derive from the complexity of the various transient interactions between zones at this location. Due to the low storage of the limestone, groundwater levels are significantly more variable than the sands aquifer which leads to model instability where the contrasts are large. The current parameterisation represents a compromise between a stable model and an acceptable groundwater level and flow calibration.

In general, the conclusion is that, whilst not ideal, the simulation of Burrows Well spring flow does match the transient patterns of observed spring flow reasonably well during flowing periods but does not manage to ‘switch off’ as rapidly as occurs in reality. Further analysis is carried out during the predictive modelling phase to determine if representing conditions closer to those observed would affect the conclusions in terms of simulated groundwater levels at Merthyr Mawr (see Section 4.6.3).

3.7.3 Pumping

Table 3.20 show results from annual monitoring data and the simulated flows over the same periods. As detailed in Section 3.1.3 calibration focussed on those periods which had complete records and where there was greater confidence in the quality of the observations.

Table 3.20 Observed and simulated flows at Cornelly quarry

	Observed Flow		Simulated Flow	
Period	Sump (m^3/day)	Offsite (m^3/day)	Sump (m^3/day)	Difference (%)
	Good data			
LTA (2001-2013)	3503[1]	-	3435	-1.9%
1 June 04 to 1 Oct 06	3382	1245	3295	2.6%
5 Aug 08 to 2 Jun 11	3735	2232	3761	-0.7%

	Poor data			
20 Jun 01 to 1 June 04	4873	1980	3559	27.0%
1 Oct 06 and 5 Aug 08	-	2281	3043	-
20 June 11 to 25 Mar 12	2969	2041	2458	17.2%

1 synthesised flow

The main inflows into Cornelly Quarry are direct recharge and groundwater inflow from the area within the cone of depression (including re-circulation from the settlement lagoon). Simulated inflows to Cornelly sump and the recirculation from the settlement lagoon are shown on Illustration 3.14.

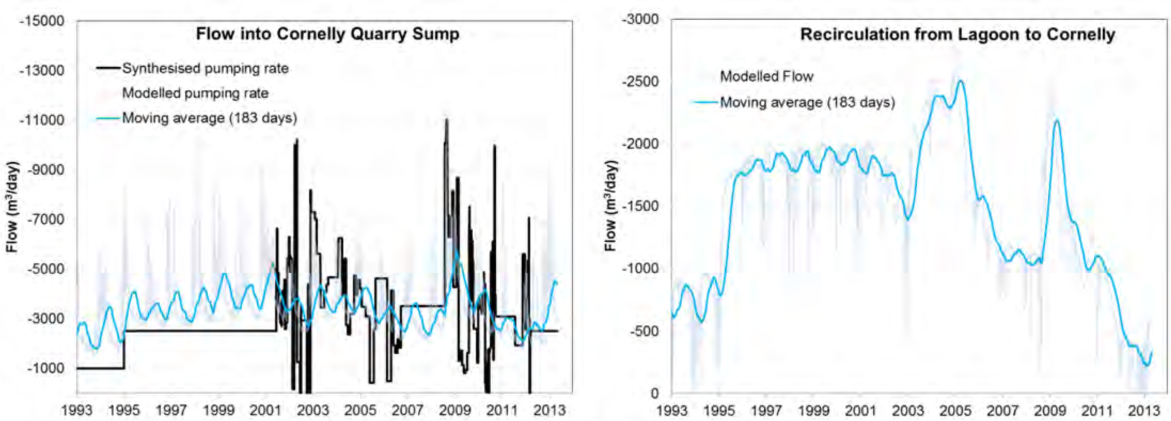


Illustration 3.14 Simulated flows at Cornelly sump

The LTA and selected data show a good agreement with the observed data and provide confidence in the model calibration. Earlier data (pre 2004) include periods of intermittent pumping when the quarry was allowed to flood. No water level measurements over this period (and less certainty in historical development depths) mean less confidence is attributed to simulated flows over this period. Records are missing between 1 Oct 2006 and 5 Aug 2008. The quality of the data post June 2011 is questionable.

Over the model calibration period re-circulation from the lagoon is typically between 1000 and 2000 m^3/day. This is broadly consistent with the difference between the sump flow and the flows pumped offsite.

3.7.4 Water balance

Model water balance

Illustration 3.15 presents the time-series water balance for each hydrogeological year (April to March) for the calibrated model. Table 3.21 summarises the model water balance over the duration of the simulation period. Average flows between zones are shown on Figure 3.4.

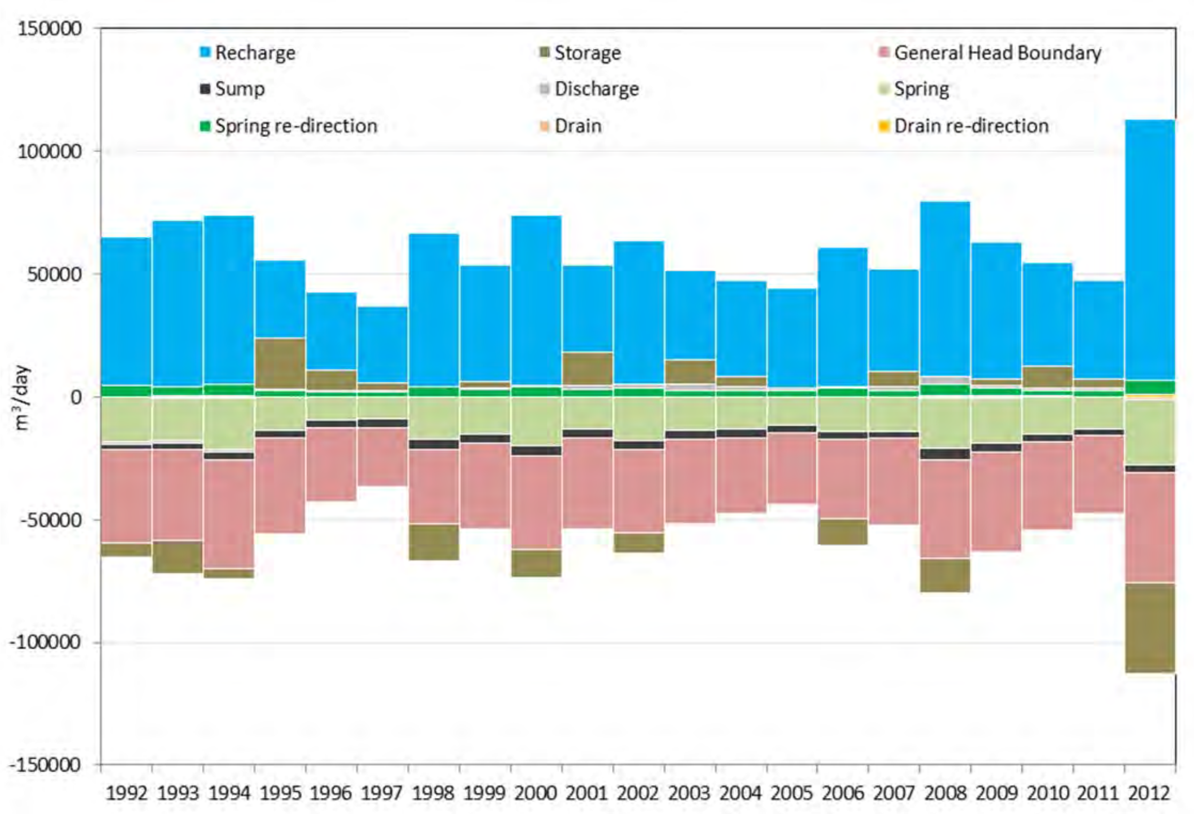


Illustration 3.15 Calibrated model water balance

Table 3.21 Model water balance over simulation period (m^3/day)

Recharge	Storage	GHB	Sump	Discharge	Spring	Drain
52,133	1,709	-35,334	-3,392	810	-15,753 (3,245)	-183 (183)

Numbers in parentheses show re-direction rates

The dominant inflow is recharge, averaging 52,000 m^3/day. A nominal inflow comprises discrete 'discharges'; the difference between consumptive abstractions and redistribution of inflow to Cornelly Quarry during historical pumping. The principal outflow is discharge to the sea via general head boundaries, which average 35,000 m^3/day, or 69% of all outflows. Spring flow (16,000 m^3/day or 31%) accounts for the remaining discharge (which comprises the discharge at New Mills Farms spring, as the flow from Burrows Well is subsequently recharged into the blown sand at Merthyr Mawr).

Kenfig water balance

Illustration 3.16 presents the time-series water balance for the Kenfig the blown sand (this excludes Kenfig Pool, other than via lateral flows and overtopping from the pool which form boundary flows to the blown sand). Table 3.22 summarises the water balance over the duration of the model period.

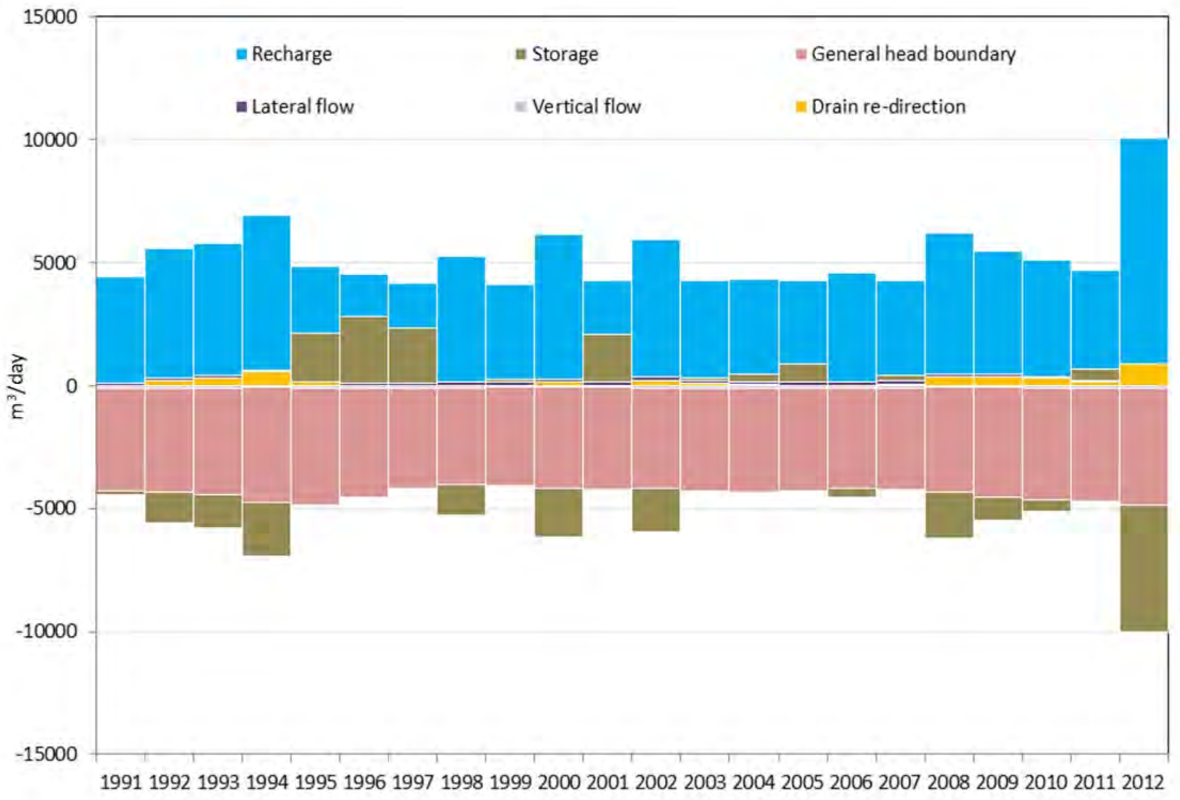


Illustration 3.16 Kenfig dune water balance

Table 3.22 Kenfig water balance over simulation period (m^3/day)

Recharge	Storage	GHB	Lateral	Vertical	Drain Re-direction
4,478	374	-4,298	104	-91	181

The dominant inflow to Kenfig blown sand system is recharge, which averages 4,500 m^3/day and amounts to approximately 94% of all inflows over the model duration (this is consistent with previous estimates (ESI,, 2004). There is a small component of lateral flow from Kenfig Pool (100 m^3/day or 2.2%). Overtopping from Kenfig pool into the blown sand also contributes a small component of inflow (180 m^3/day or 3.8%). Groundwater flow through the blown sand and discharge to the sea is the main component of outflow, with a small component of downward leakage into the underlying sands and gravels (90 m^3/day or 2.0%).

Merthyr Mawr water balance

Illustration 3.17 presents the time-series water balance for the blown sand at Merthyr Mawr. Table 3.23 summarises the water balance over the duration of the model period.

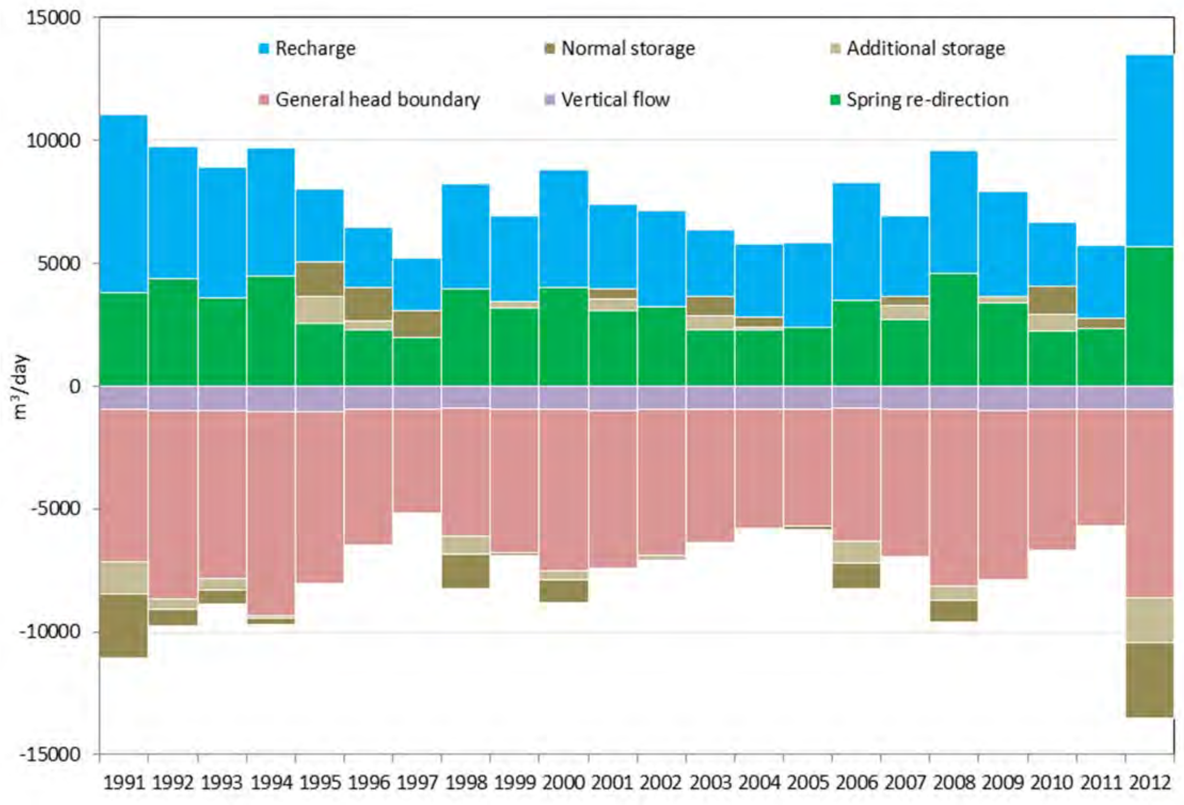


Illustration 3.17 Merthyr Mawr dune water balance

Table 3.23 Merthyr Mawr water balance over simulation period (m^3/day)

Recharge	Spring re-direction	Normal storage	Additional storage	GHB	Vertical
4,010	3,252	-120	-81	-6,101	-960

Spring flows at Burrows Well account for 3,300 m^3/day (45 %) of the total inflow to the dune system, with direct recharge contributing the remainder (4,000 m^3/day or 55 %). The principal outflow from the blown sand is discharge to the sea (6,100 m^3/day or 86%) with a significant proportion also lost via downward leakage to the underlying Carboniferous Limestone (960 m^3/day or 14%).

3.8 Model Validation

The model was validated by checking to see what effect it predicts if there was no quarry dewatering. Although there are no reliable groundwater level data for the period prior to the start of dewatering at Cornelly Quarry, anecdotally this is thought to be around 60 mAOD. The validation test shows that groundwater levels around Cornelly quarry rise from an average of 25.7 mAOD to around 52.6 mAOD over the simulated period (range 42.1-81.0 mAOD). This provides some additional confidence in the ability of the model to predict heads correctly over a wide range of conditions.

3.9 Sensitivity Analysis

A formal sensitivity analysis was carried out to investigate the level of uncertainty associated with several aspects of the model calibration. Previous phases of investigation have succeeded in clarifying many aspects of the conceptual understanding of the system, but several aspects related to the connections between the dune sand aquifers and underlying geology at Kenfig, and the conceptual representation of the dune system at Merthyr Mawr are unclear. In summary, these uncertainties include:

- The extent, thickness and hydraulic conductivity of the estuarine clay underlying the blown sand system and pool at Kenfig.
- The extent, thickness and hydraulic conductivity of the till underlying the glaciofluvial deposits at Kenfig.
- The connectivity of the glaciofluvial deposits at Kenfig to the coast.
- Lateral connection between glaciofluvial deposits and Kenfig pool (ephemeral seeps).
- Lateral connection between Kenfig pool and the blown sand.
- The thickness and hydraulic conductivity of the till underlying the blown sand system at Merthyr Mawr.
- The connectivity of the blown sand at Merthyr Mawr to the coast.
- The role of pool storage at Merthyr Mawr.

A more detailed list of the sensitivity runs is shown in Table 3.25. The sensitivity runs were designed in consultation with technical staff including detailed discussions with NRW in 2013.

3.9.1 Sensitivity results

Discussion with Natural Resources Wales had highlighted the need for sensitivity analysis in order to ensure that the model parameterisation could be justified. Where this revealed some element of model equivalence, this was then taken forward to the sensitivity analysis of predictive scenarios. Table 3.24 summarises the parameters that have been carried through to a sensitivity analysis on the predictive runs.

For each sensitivity run a comparison is made between the simulated changes in conditions and the calibrated model. A summary of the model sensitivity results due to the modifications to the conceptual model is outlined in Table 3.25.

A more detailed description of the sensitivity results are shown in Table 3.26-Table 3.31. The graphs in these tables show the difference in the simulated groundwater levels between the calibrated model and the results due to each particular variation in model parameterisation. Selected results are shown for Zone 51 (Glaciofluvial deposits) and Zone 56 (Blown Sand) at Kenfig. At Merthyr Mawr model results are shown for Zone 33 (Carboniferous Limestone) and Zone 45 (Blown Sand).

Table 3.24 Sensitivity runs in the predictive phase

Zones	Prediction	Sensitivity	Parameter		Unit	Calibrated	Sensitivity
42	SENS1	17.2	V	Pool storage	m^3	5262	10524
42	SENS2	17	V	Pool storage	m^3	5262	2631
48-53	SENS3	4.1	K	Estuarine Clay	m/d	$1.33x10^{-5}$	$2.00x10^{-5}$
46-53	SENS4	12.2	T	Alluvium	m^2/d	9.54	6.93
47-53	SENS5	11.2	T	Alluvium	m^2/d	$1.20x10^{1}$	8.87
53,55-57	SENS6	13.1	T	Alluvium	m^2/d	$3.55x10^{1}$	$2.69x10^{1}$
47-38	SENS7	9.1	K	Till	m/d	$1.62x10^{-4}$	$2.25x10^{-4}$
all	SENS8	n/a	R+T			-	+ 15%
all	SENS9	n/a	R+T			-	-15%

V pool storage; K bulk vertical hydraulic conductivity; T bulk transmissivity; R recharge

Table 3.25 Summary of model sensitivity runs

Run	Area	Zone	Parameter	Unit	Calibrated	Parameter range	Comment
1	Kenfig	46-53	Till	m/d	1.0×10^{-5}	K_v inc. $1.6\times10^{-4} – 6.0\times10^{-4}$	An increase in bulk vertical hydraulic conductivity of the till improves the connection between the GFD and underlying solid geology, allowing groundwater to drain downwards. Groundwater levels decrease in all zones with the exception of the underlying solid geology. The blown sand experience a drop of up to 10cm over the modelled parameter range.
2	Kenfig	50-52	Till coastal	m^2/d	5.0×10^{-2}	T inc./dec. 7.0×10^{-3} – 1.0×10^{-2}	Model calibration is extremely sensitive to the lateral connection which controls the discharge between the GFD and the coast. In the calibrated model till is assumed to limit this connection at the seaward boundary. Increasing the bulk transmissivity allows more water to leave the model from the GFD. Groundwater levels are significantly reduced in the GFD, which in turn increase the downward leakage from the overlying the blown sand. Conversely, a reduction in till transmissivity produces a groundwater level increase in the effected zones. A low transmissivity connection is required to maintain adequate model calibration.
3	Kenfig	46-53	Till	m/d	1.0×10^{-5}	K_v dec. 1.3×10^{-4} – 1.6×10^{-4}	A decrease in the bulk hydraulic conductivity of the till causes increased groundwater levels in all cells above the till and a reduction in groundwater levels in the underlying solid geology. An increase of 10cm is simulated within the blown sand for the maximum decrease in vertical connectivity.
4	Kenfig	46-53	Estuarine Clay	m/d	5.0×10^{-5}	K inc. 4.0×10^{-5} – 1.3×10^{-4}	The low K lacustrine layer beneath the blown sand is necessary to keep the dune sand aquifer perched. Increasing the bulk vertical hydraulic conductivity causes water to drain from the perched aquifer and increase groundwater levels in all underlying layers.
5	Kenfig	46-53	Estuarine Clay	m/d	5.0×10^{-5}	K dec. 2.0×10^{-5} – 3.0×10^{-5}	The low K lacustrine layer beneath the blown sand is necessary to keep the dune sand aquifer perched. Decreasing the bulk vertical hydraulic conductivity reduces groundwater levels in underlying zones, as groundwater is retained within the blown sand and downward leakage is reduced.
6	Kenfig	57	Estuarine Clay	m/d	5.0×10^{-5}	K inc. $3.0\times10^{-5} – 1.3\times10^{-4}$	Increasing the connectivity between the northern dunes and the GFD causes effects as described in Run 4, but more localised. Groundwater levels in the blown sand drop by several cm for the maximum increase in parameter values.
7	Kenfig Pool	53	Estuarine Clay	m/d	5.0×10^{-5}	K inc. $1.3\times10^{-5} – 1.3\times10^{-4}$	Increasing bulk hydraulic conductivity beneath the pool causes a decrease in pool and dune sand groundwater levels. A subsequent increase in groundwater levels in the underlying GFD and solid geology is simulated due to increased downward leakage, although changes are typically less than 4cm.
8	Kenfig Pool	53	Estuarine Clay	m/d	5.0×10^{-5}	K dec. $1.3\times10^{-5} – 1.2\times10^{-5}$	Decreasing bulk hydraulic conductivity beneath the pool causes an increase in pool land the blown sand groundwater levels. A subsequent decrease in groundwater levels in underlying GFD and solid geology is simulated due to decreased downward leakage, although changes are typically less than 4cm.
9	Kenfig	38	Till	m^2/d	2.0×10^{-5}	K inc./dec. 1.3×10^{-4} – 6.0×10^{-4}	Increasing bulk hydraulic conductivity of the till causes groundwater levels in the GFD to decrease as more groundwater drains into the underlying MMMF, where groundwater levels subsequently increase. The opposite effects are simulated for a bulk with decreased till vertical hydraulic conductivity. All simulated changes in groundwater levels are less than 10 cm.
10	Kenfig	25	Till	m/d	1.2×10^{-1}	K dec. $1.6\times10^{-5} – 1.2\times10^{-1}$	Decreasing the vertical connection between the GFD and CL causes increase groundwater levels within the blown sand and the GFDs. Changes in groundwater levels are typically large (up to 1.5m) in all zones.
11	Kenfig	47	Alluvium	m^2/d	5.0×10^{-1}	T inc./dec. 8.9×10^{0} - 2.7×10^{1}	Increasing the transmissivity (lateral seeps) between the GFDs (Zone 47) and Kenfig pool (Zone 53) produces model instability at high parameter values (>27m^2/day). Long term trends show a decrease in groundwater levels in the GFDs. A decrease in transmissivity produces the opposite effect in all cells. All changes are relatively small (<15cm). Kenfig pool shows little change (+/- 1cm).
12	Kenfig	46	Alluvium	m^2/d	5.0×10^{-1}	T inc./dec. $6.9\times10^{0} – 2.4\times10^{1}$	Increasing the transmissivity (lateral seeps) between the GFDs (Zone 46) and Kenfig pool (Zone 53) produces model instability at high parameter values (>24m^2/day). Long term trends show a decrease in groundwater levels in the GFDs and the blown sand (<5cm). A decrease in transmissivity produces the opposite effect in all cells. All changes are relatively small (<15cm). Kenfig pool shows little change (+/- 1cm).
13	Kenfig	55-56	Alluvium	m^2/d	5.0×10^{-1}	T inc. $3.6\times10^{1} – 2.7\times10^{1}$	Increasing the transmissivity from Kenfig Pool to the blown sand produce peaks/troughs during 1998/1999 at Kenfig Pool, GFDs and underlying solid geology. The blown sand show a modest decrease in groundwater levels. Zone 55 (which receives overtopping water from Kenfig Pool) shows a decrease in groundwater levels. Changes are typically small (<5cm) in all zones.
14	Kenfig	55-56	Alluvium	m^2/d	5.0×10^{-1}	T dec. $3.2\times10^{1} – 4.1\times10^{1}$	Decreasing the transmissivity from Kenfig Pool to the blown sand produces peaks/troughs during 1998/1999 at Kenfig Pool, GFDs and underlying solid geology. The blown sand show a modest increase in groundwater levels. Zone 55 which receives overtopping water from Kenfig Pool shows an increase in groundwater levels. Changes are typically small (<5cm) in all zones.
15	Kenfig	55-57	Initial heads	m	-	Initial head inc./dec. ±1	An increase and decrease in initial heads in the blown sand caused up to a 10cm change in groundwater levels in the GFD. Groundwater levels returned to their previous values over the simulation period.
16	Merthyr Mawr	42-45	Till	m/d	7.0×10^{-4}	K inc./dec. 4.0×10^{-4} – 1.3×10^{-3}	Groundwater levels in the blown sand are very sensitive to the bulk hydraulic conductivity of the till. A ±0.5m change in thickness (an increase or decrease in bulk conductivity) produces a decrease/increase of up to 1.0m in dune sand groundwater levels. The model failed when the thickness of the till was reduced to less than 0.4m (bulk hydraulic conductivity >1.3×10^{-3})
17	Merthyr Mawr	42/43	Pool storage	m^3	5262 1000000	Volume inc./dec. 2631 – 5262 13879 - 41637	Increasing and decreasing the pool storage at Merthyr Mawr by 50% changed groundwater levels by up to 4.5m. Mass balance errors occurred where less storage was available than spring discharge requiring an arbitrarily large value to be assigned to the lower pool. Variation of the top pool parameters alone was less sensitive to change.
18	Merthyr Mawr	43-45	Sand	m/d	20	T inc./dec. 17 – 23	The model is very sensitive to the depth dependent transmissivity of the lateral connection between the blown sand and the coast. Increasing the hydraulic conductivity (transmissivity) allows more water to leave the model, decreasing groundwater levels in all zones (and vice versa). A 15% change in the hydraulic conductivity produces change up to 0.5m in the sands and underlying limestone.

GFD: glaciofluvial deposits; MMMF Mercia mudstone marginal facies; CL Carboniferous limestone

Table 3.26 Sensitivity analyses results (Runs 1-3)

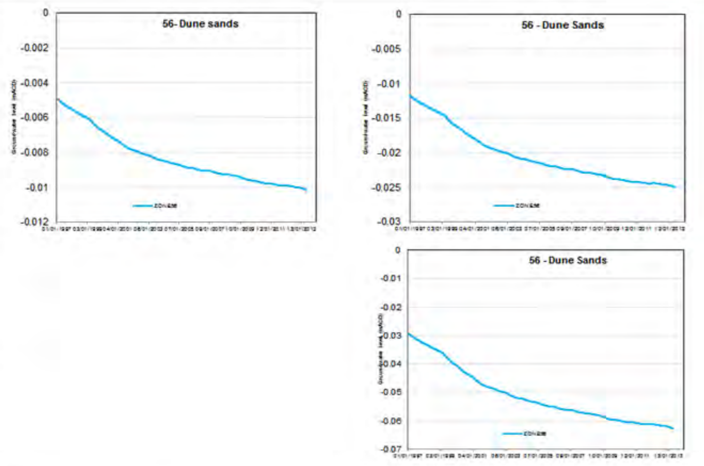
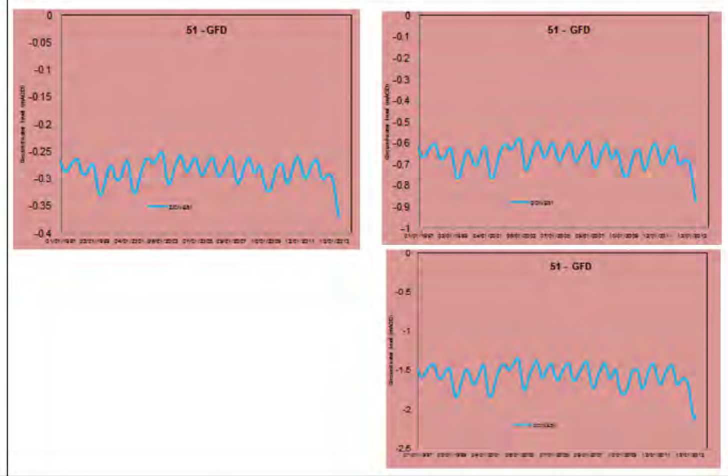
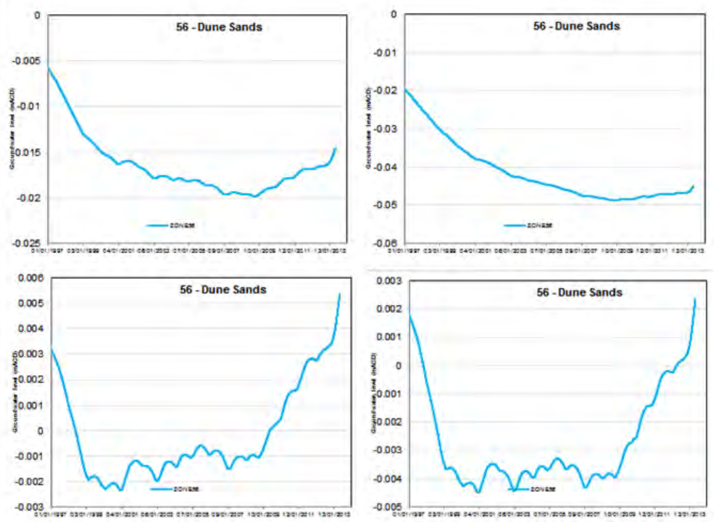
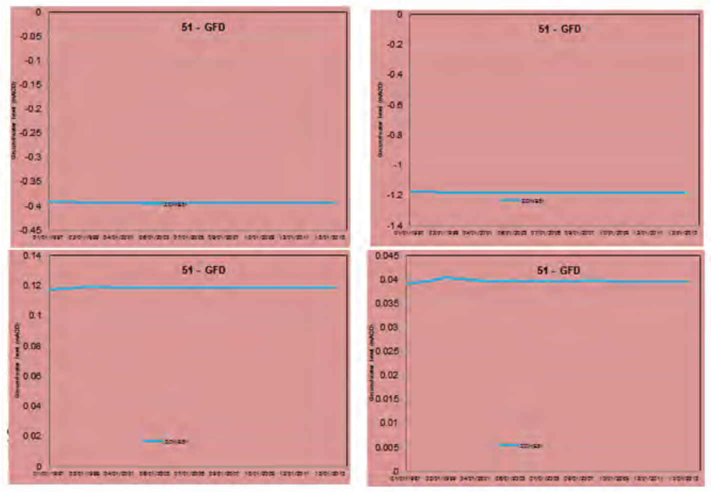
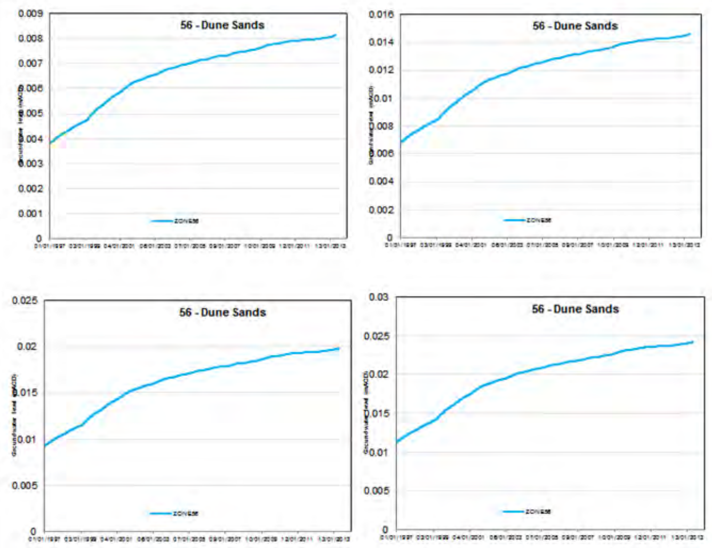
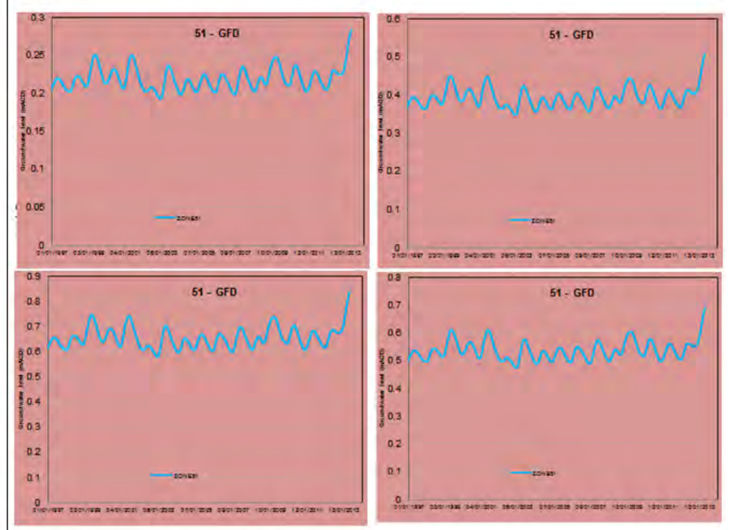
Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.0001	8	1.62E-04			
1	**0.0001**	**6**	**1.83E-04**	-		
1.1	**0.0001**	**4**	**2.25E-04**	-		
1.2	**0.0001**	**1**	**5.98E-04**	-		
Calibration	-	8	0.01 (lateral)	0.00016 (vertical)		
2		**8**	**2.00E-02**	**1.60E-04**		
2.1		**8**	**4.00E-02**	**1.60E-04**		
2.2		**8**	**9.00E-03**	**1.60E-04**		
2.3		**8**	**7.00E-03**	**1.60E-04**		
Calibration	0.0001	8	1.62E-04			
3	**0.0001**	**10**	**1.50E-04**	-		
3.1	**0.0001**	**12**	**1.42E-04**	-		
3.2	**0.0001**	**14**	**1.36E-04**	-		
3.3	**0.0001**	**16**	**1.31E-04**	-		

Table 3.27 Sensitivity analyses results (Runs 4-6)

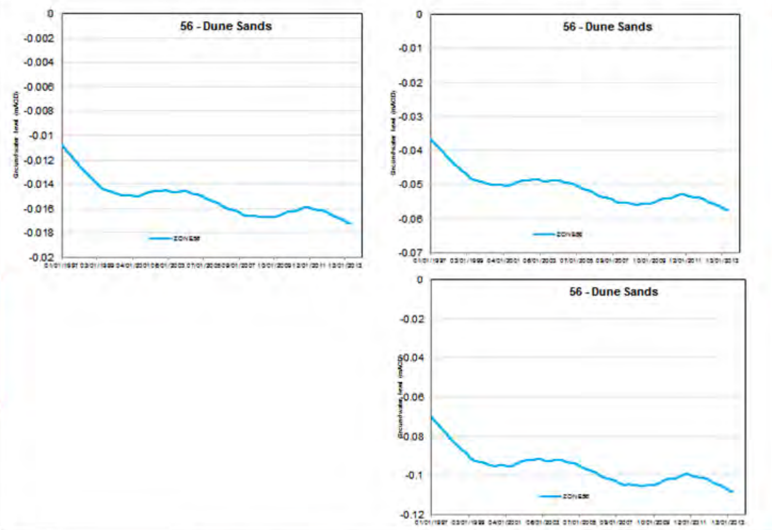
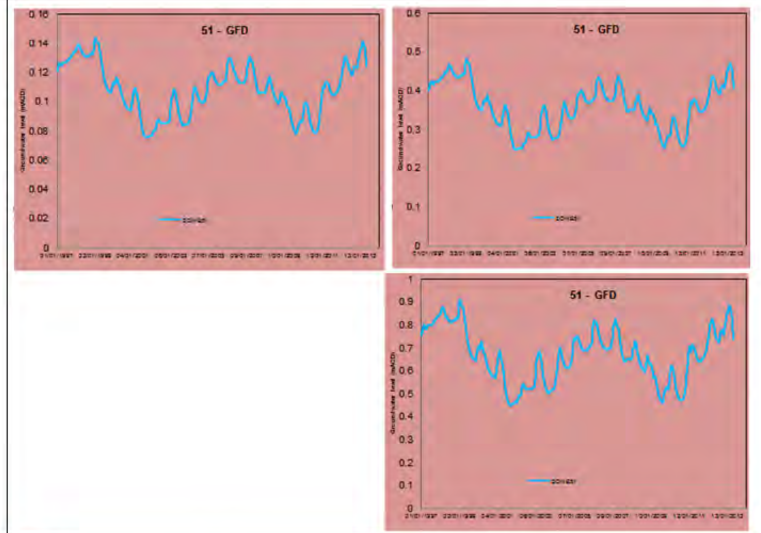
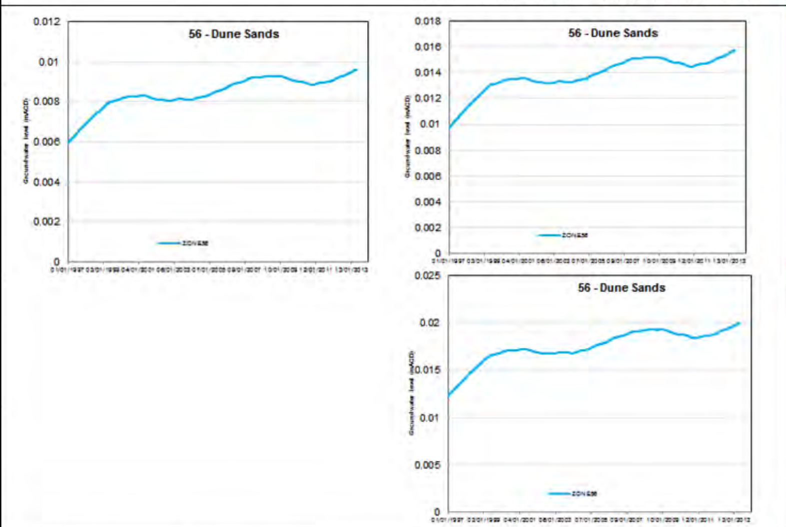
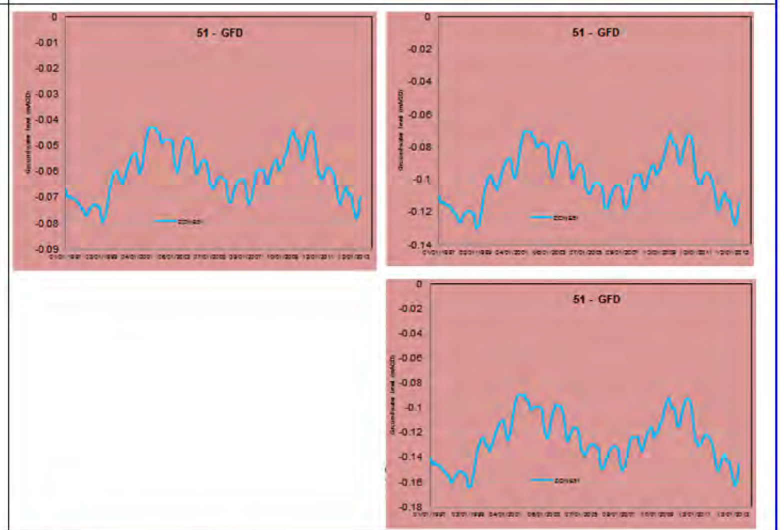
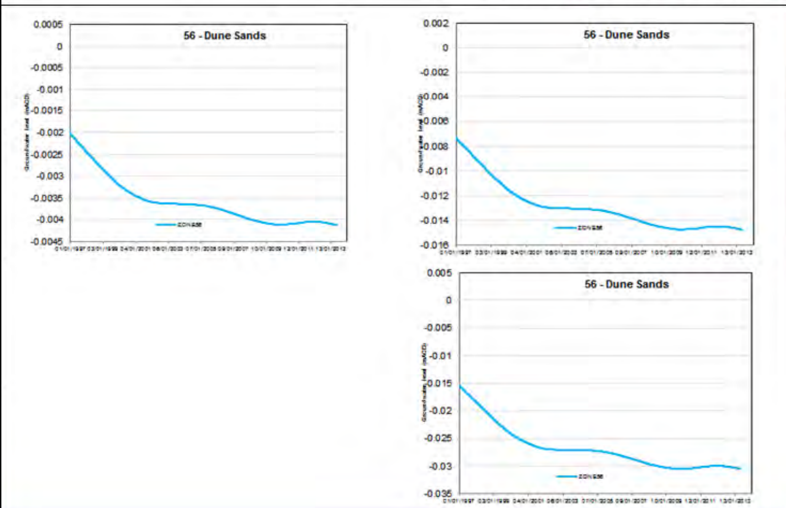
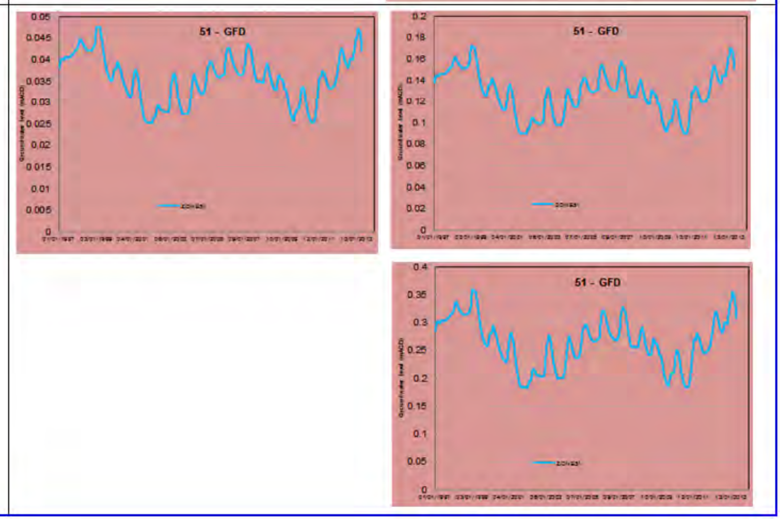
Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.00001	3	Under Pool T 1.33E-05	Under Sands T 3.00E-05		
4	0.00001	2	1.50E-05	4.00E-05		
4.1	0.00001	1	2.00E-05	7.00E-05		
4.2	0.00001	0.5	3.00E-05	1.30E-04		
Calibration	0.00001	3	Under Pool T 1.33E-05	Under Sands T 3.00E-05		
5	0.00001	4	1.25E-05	2.50E-05		
5.1	0.00001	5	1.20E-05	2.20E-05		
5.2	0.00001	6	1.17E-05	2.00E-05		
Calibration	0.00001	3	3.00E-05			
6	0.00001	2	4.00E-05	-		
6.1	0.00001	1	7.00E-05	-		
6.2	0.00001	0.5	1.30E-04	-		

Table 3.28 Sensitivity analyses results (Runs 7-9)

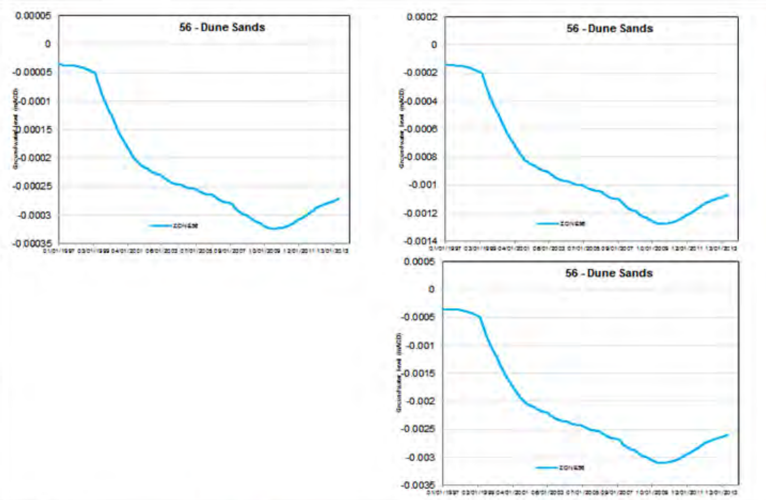
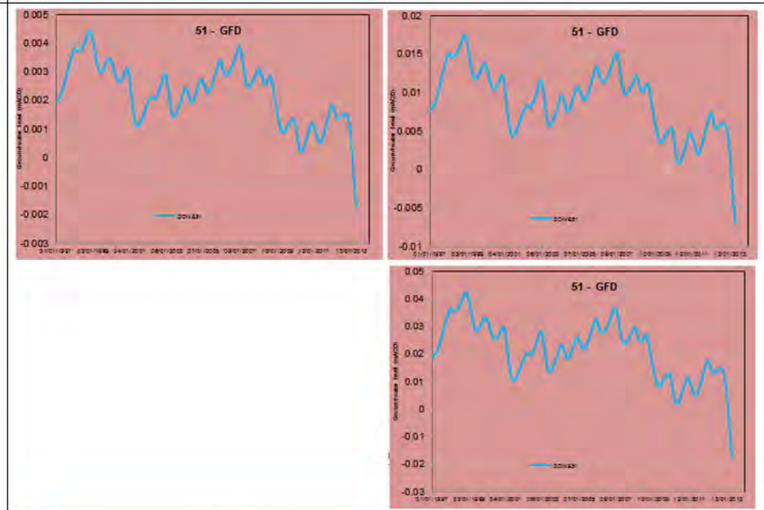
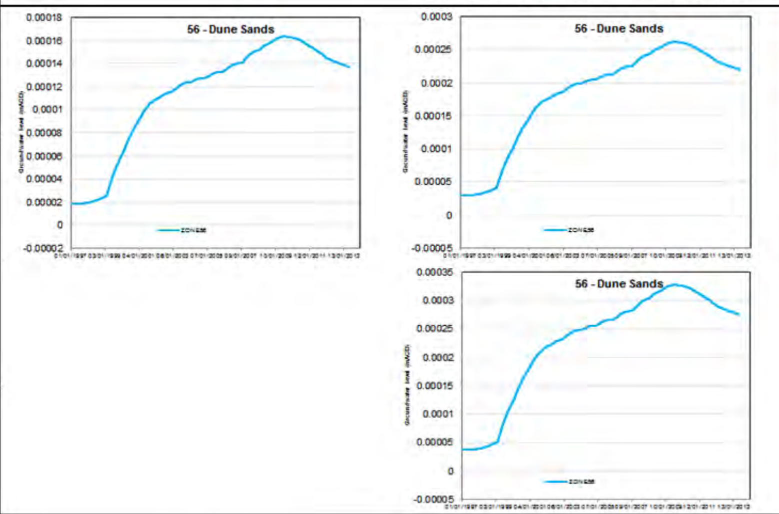
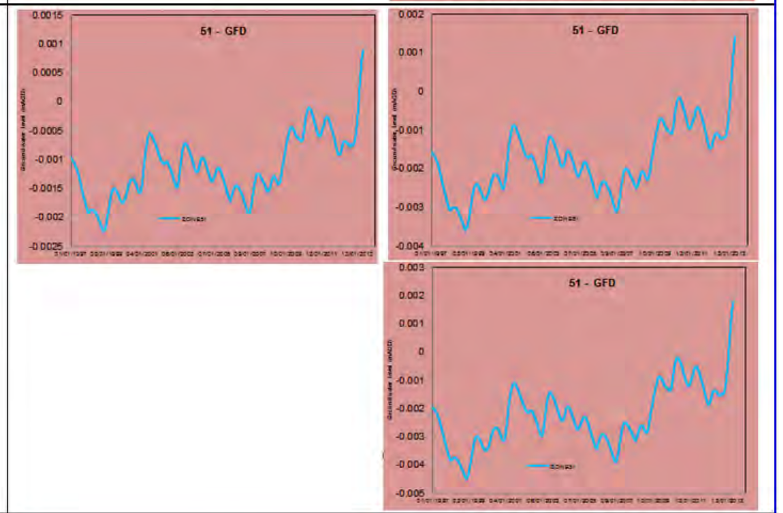
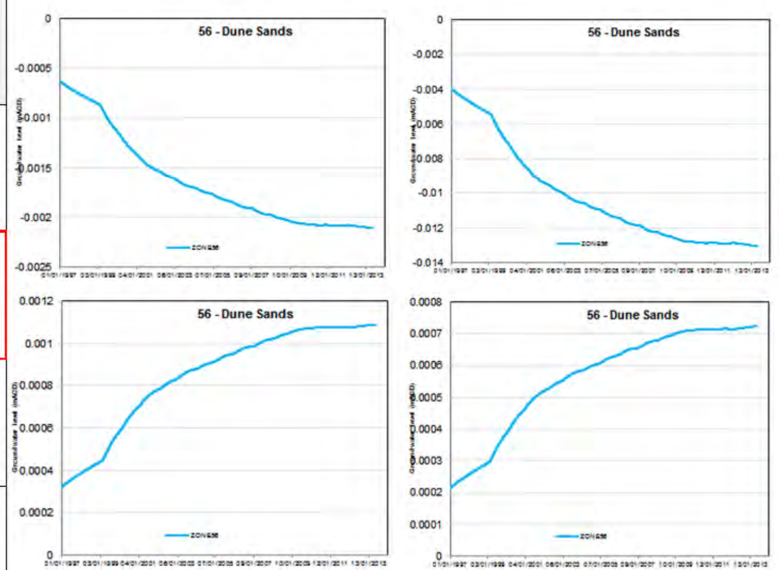
Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.00001	3	1.33E-05	-		
7	**0.00001**	**2**	**4.00E-05**	-		
7.1	**0.00001**	**1**	**7.00E-05**	-		
7.2	**0.00001**	**0.5**	**1.30E-04**	-		
Calibration	0.00001	3	1.33E-05	-		
8	**0.00001**	**4**	**1.25E-05**	-		
8.1	**0.00001**	**5**	**1.20E-05**	-		
8.2	**0.00001**	**6**	**1.17E-05**	-		
Calibration	0.0001	8	1.62E-04	-		
9	**0.0001**	**4**	**2.25E-04**	-		
9.1	**0.0001**	**1**	**5.98E-04**			
9.2	**0.0001**	**12**	**1.42E-04**	-		
9.3	**0.0001**	**16**	**1.31E-04**	-		

Table 3.29 Sensitivity analyses results (Runs 10-12)

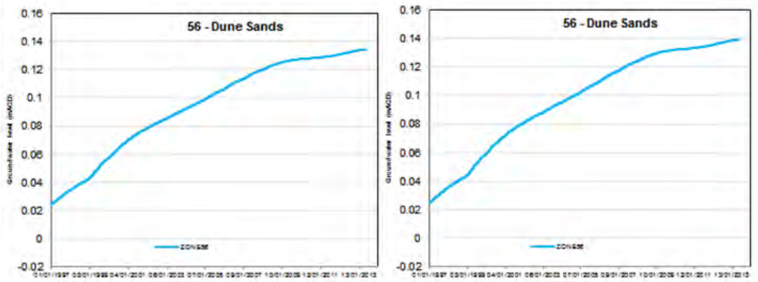
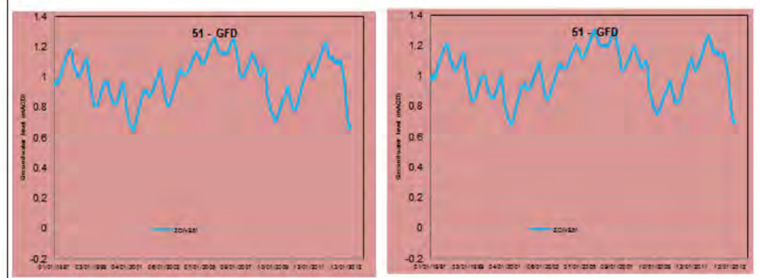
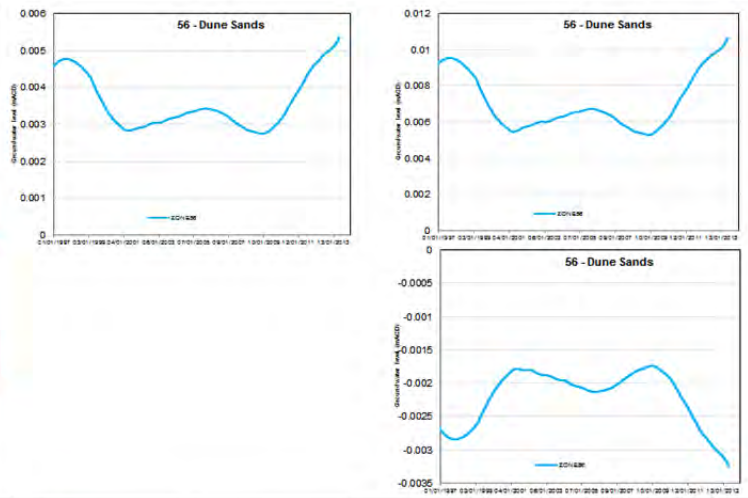
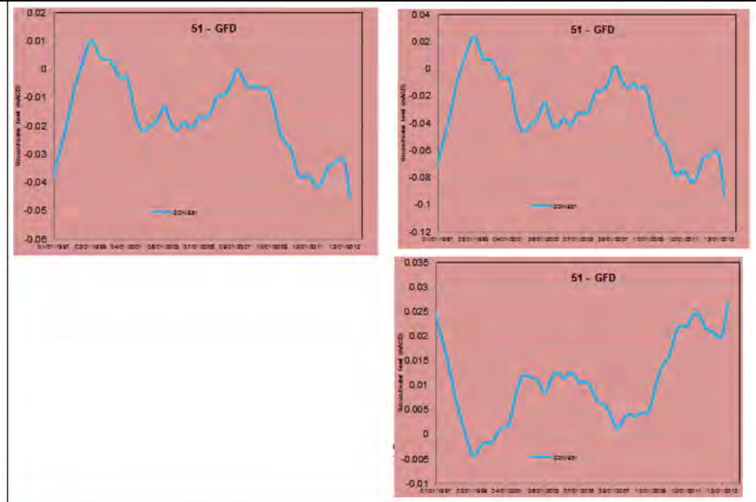
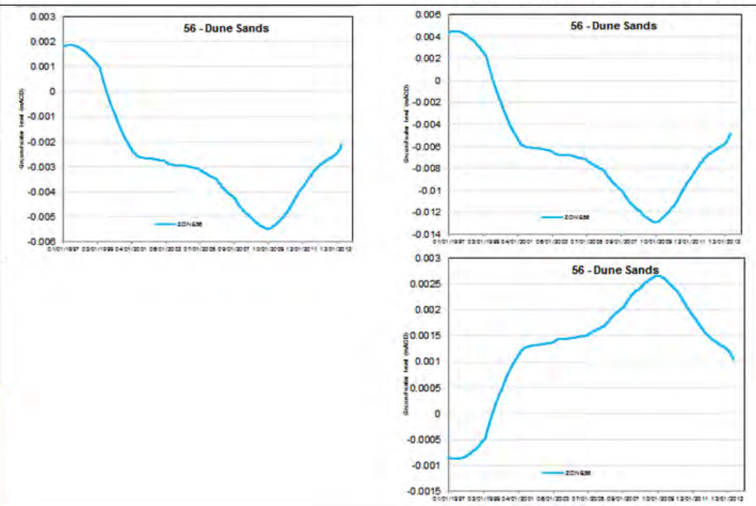
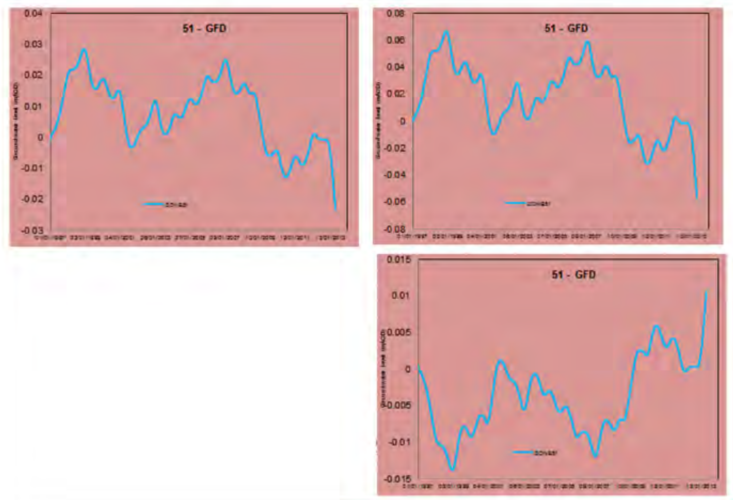
Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.0001 (till)	0	1.19E-01	-		
10	**0.0001**	**1**	**6.00E-05**			
10.1	**0.0001**	**8**	**1.62E-05**			
Calibration	0.1	1	1.20E+01			
11	**0.1**	**0.5**	**1.84E+01**	-		
11.1	**0.1**	**0.2**	**2.72E+01**	-		
11.2	**1.00E-01**	**1.5**	**8.87E+00**	-		
Calibration	0.1	1	9.54E+00			
12	**0.1**	**0.5**	**1.54E+01**	-		
12.1	**0.1**	**0.2**	**2.44E+01**	-		
12.2	**0.1**	**1.5**	**6.93E+00**	-		

Table 3.30 Sensitivity analyses results (Runs 13-15)

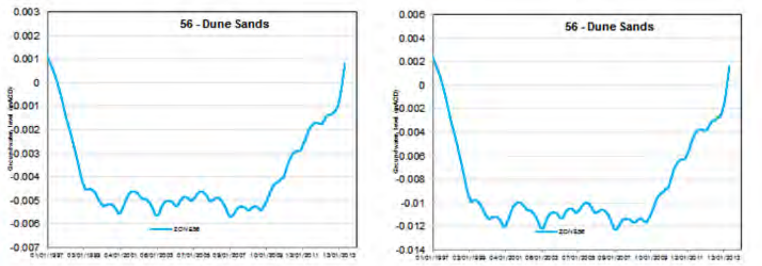
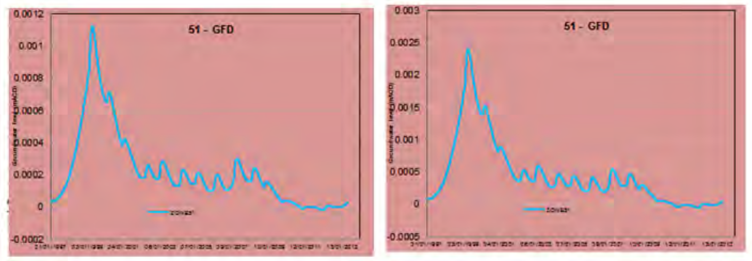
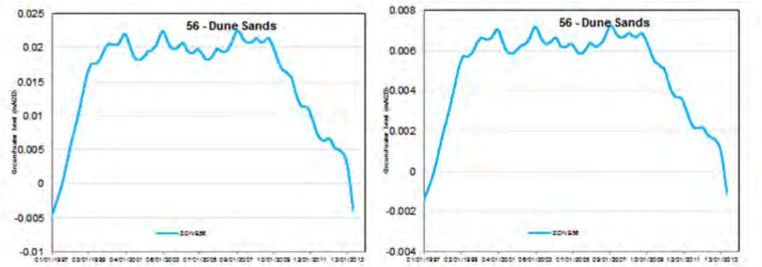
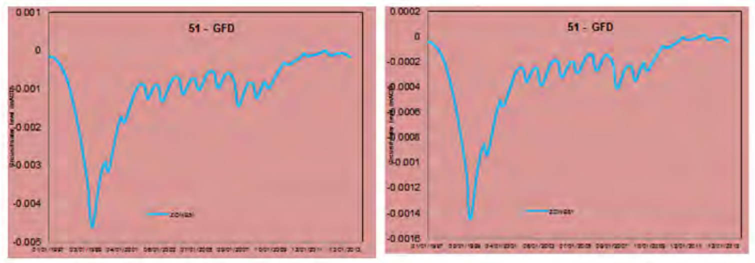
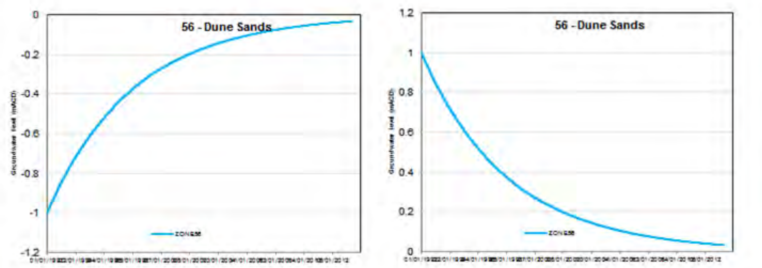
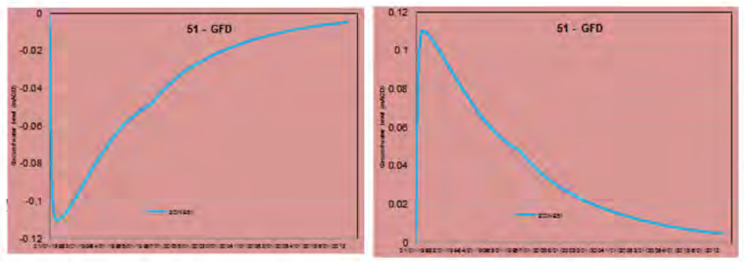
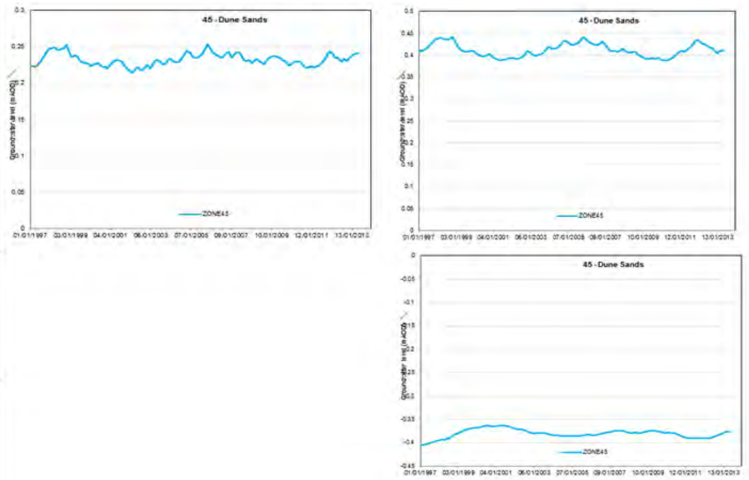
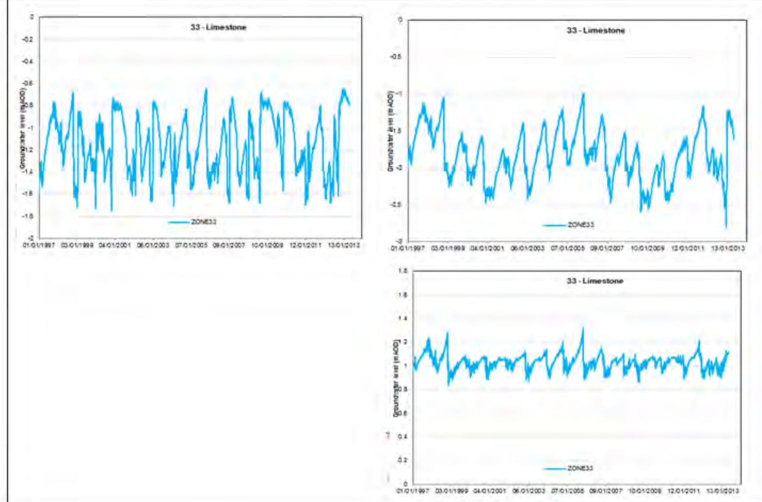
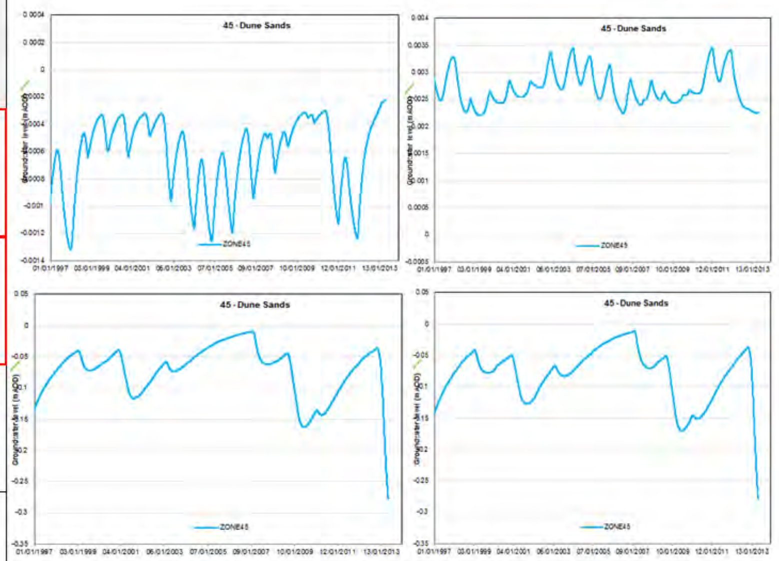
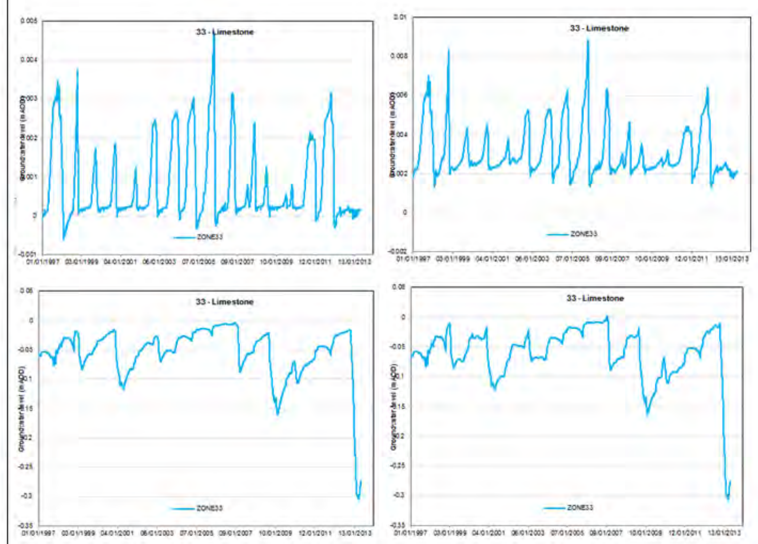
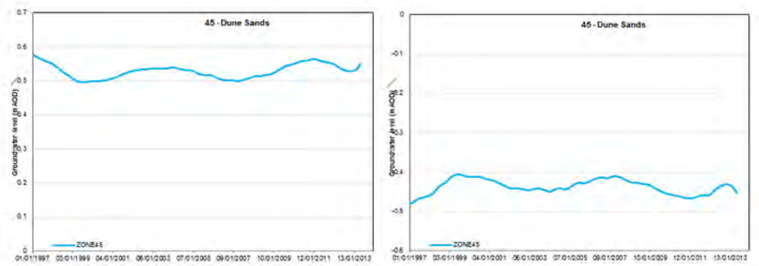
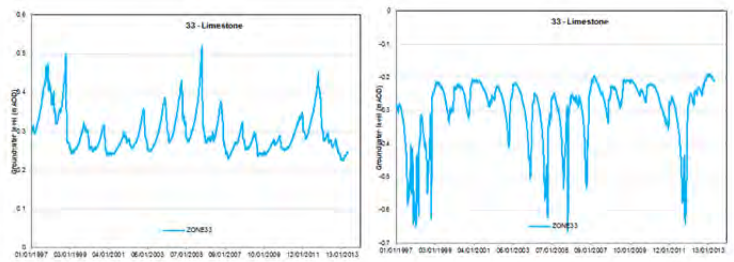
Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.1	1	3.55E+01			
13	**0.1**	**1.2**	**3.15E+01**	-		
13.1	**0.1**	**1.5**	**2.69E+01**	-		
Calibration	0.1	1	3.55E+01			
14	**0.1**	**0.5**	**5.24E+01**	-		
14.1	**0.1**	**0.8**	**4.08E+01**	-		
Calibration	Heads 10mAOD					
15	**9**					
15.1	**11**					

Table 3.31 Sensitivity analyses results (Runs 16-18)

Number	Hydraulic Conductivity (m/d)	Layer Thickness (m)	Transmissivity (m2/d)	Second area Transmissivity (m2/d)	Dune Sands (Graphs in numerical order clockwise from top left)	Glaciofluvial Deposits/Limestone (Graphs in numerical order clockwise from top left)
Calibration	0.0001	1	7.00E-04			
16	0.0001	1.5	5.00E-04			
16.1	0.0001	2	4.00E-04			
16.2	0.0001	0.5	1.30E-03			
Calibration	5262m2 (cell 42)	27758m2 (cell 43)				
17	2631	27758				
17.2	10524	27758				
17.3	5262	13879				
17.4	5262	41637				
Calibration	Heads 20mAOD	-	-			
18	17					
18.1	23					

4 MODEL PREDICTIVE SCENARIOS

Having derived an acceptable model calibration, the model provides a tool that allows theoretical effects of quarrying activities to be assessed. The model can be used to estimate the difference between groundwater levels and flows for a baseline condition with those levels derived for any relevant quarrying scenario (i.e. the model predictions).

The model set up for the baseline and predictive scenarios are described further in the following sections. Detailed results of the predictive scenarios are described in Appendix 7.4.

4.1 Initial model set-up

The climate sequence and initial conditions uses in the baseline and predictive scenarios are shown schematically on Illustration 4.1 below.

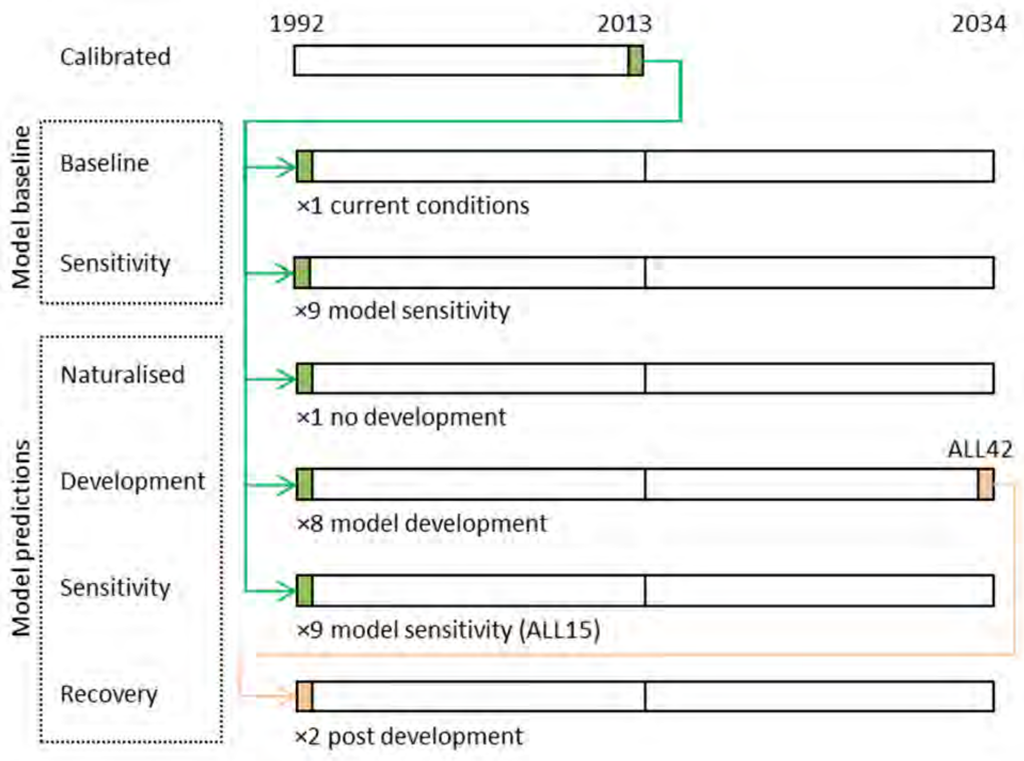


Illustration 4.1 Model baseline and predictive runs

4.1.1 Climate sequence

A future climate sequence for the baseline and predictive scenarios has been constructed from the 21 year climate sequence (1992-2013) used in the calibrated model. In order to extend the climate sequence to cover the full development period (42 years), the 21 year historical sequence has been repeated twice.

4.1.2 Initial conditions

The final heads (1 Jan 2013) from the calibrated model are used to define the initial conditions for the baseline simulation which covers the full 42 year development period. Predictive naturalised and development scenarios have the same climatic sequence and starting heads as the baseline model against which they are to be compared. The recovery model uses the final heads (1 Jan 2034) at the end of development period to see what effect it predicts following quarry development. An equivalent baseline model can be constructed for each set of model parameters brought forward from the formal sensitivity analyses and their predictive runs similarly defined.

4.2 Model Baseline

The model baseline represents the current stage of quarry development against which future development runs can be compared. Cornelly is actively dewatering and the current development depth is constant throughout the simulation at -3 mAOD. It is assumed that all groundwater entering Cornelly quarry sump (Zone 4) is pumped to Grove (Zone 27). Grove and Gaens are not actively dewatering.

4.3 Naturalised run

The naturalised run is a theoretical estimate of what conditions might have been in the absence of any quarry development. Model parameterisation is identical to the calibrated model with the exception that Cornelly sump is deactivated in Zone 4. It does not include the effects of quarry storage.

4.4 Development runs

The groundwater model has been used to carry out predictive simulations for eight development scenarios. The development of the quarries is considered at two future stages;

1) at the end of the 15 year ROMP cycle, and;

2) development at 42 years.

These development stages are undertaken for each quarry in isolation, with two further runs considering the combined development of the three quarries. The development scenarios can be summarised as follows:

- 15 and 42 year development at Cornelly (CN15, CN42)
- 15 and 42 year development at Grove (GR15, GR42)
- 15 and 42 year development at Gaens (GA15, GA42)
- 15 and 42 year development combined (ALL15 and ALL42).

For each development run the sump level for the active quarries at the given stage are set at the appropriate development depths (see Table 4.3). 'No dewatering' indicates that the sump in the respective quarry is set to inactive. The disposal location for Cornelly quarry (Zone 4) operating in isolation is to Grove (Zone 27). Grove in isolation pumps to the railway cuttings (Zone 26) and Gaens (Zone 16) in isolation discharges to the sink holes north-west of the quarry (Zone 23). For the combined development scenarios the discharge location from Grove and Gaens remain the same, whereas Cornelly pumps to Pant Mawr (Zone 7).

4.5 Recovery runs

Recovery modelling was undertaken to simulate effects following the maximum development of all three quarries (i.e. end of run ALL42). Recovery is simulated by ceasing abstraction from the sumps and adding additional storage capacity into the relevant zones to represent open water as the quarry refills (see Table 4.1).

Table 4.1 Additional storage areas in recovery runs

Zone	Elevation (mAOD)	Fractional area (-)	Storage (-)	Description
4	-75.0	0.64	1.0	Cornelly
16	-20.0	0.42	1.0	Gaens
27	-15.0	0.33	1.0	Grove

The additional storage capacity was introduced as discussed in Section 2.8. Quarry areas, as a fraction of each zone, were estimated from development plans.

Initial conditions used in all zones (other than the quarries) are groundwater levels from the end of the combined development run ALL42. Note that the radial flow approximation used to simulate quarry pumping cannot work in reverse (no sump level is defined). As such, inflows to the quarry zones are determined conventionally and would be significantly overestimated if the initial head in the quarry zone were set at the maximum development depths. An iterative approach was adopted to gradually increase the starting heads in each quarry zone to match the radial inflows at the end of the development run ALL42. Initial heads used in the recovery runs in comparison to the final heads from run ALL42 are summarised in Table 4.2.

Table 4.2 Initial quarry heads in recovery runs

Zone	All42 (mAOD)	Recovery (mAOD)	Description
4	-75.0	-10.0	Cornelly
16	-20.0	0.0	Gaens
27	-15.0	0.0	Grove

Two separate recovery models were developed:

1) no mitigation measures are in place, and

2) mitigation with some residual pumping for the initial 10 years of recovery.

- 50% Cornelly pumping rate to the railway springs (1496 m^3/day)
- 50% Grove pumping rate to the railway springs (819 m^3/day)

Additional runs to optimise the mitigation have not been carried out as the final quarry configuration is not yet clear.

4.6 Sensitivity runs

4.6.1 Conceptual and parameter uncertainty

Following the formal sensitivity analysis (Section 3.9), the parameters that were not fully constrained by the model calibration were carried through to the predictive runs. A new baseline scenario is developed for each of these sensitivity runs for the given model parameterisation. The predictive sensitivity runs are all based on the 15 year development run for the combined quarry development (ALL15).

The sensitivity of the simulated changes to model parameterisation (i.e. the difference between the sensitivity run and its sensitivity baseline compared with the difference between the ALL15 run and the main baseline run) are subsequently assessed.

4.6.2 Model equivalence

In addition to conceptual and parameter uncertainty, there remains a level of uncertainty due to model equivalence regarding the calibrated values for recharge and transmissivity. Recharge and transmissivity are influential model parameters and an approach is required to fully examine the likely range to which transmissivity has been constrained. .

An agreed upon approach has been to undertake two sensitivity runs with an increase and decrease in recharge throughout the model by 15% (this is the largest change in recharge relative to the best estimate that is considered to be credible). To ensure that groundwater heads are maintained at their approximate calibration position, the transmissivity was also increased and decreased by 15% throughout the respective models. This therefore provides sensitivity analysis with the highest and lowest transmissivity broadly consistent with the current conceptual model.

4.6.3 Burrows Well

A further sensitivity analysis was undertaken to investigate the adequacy of the model representation at Burrows Well (see Section 3.7.2).

For the calibrated model, the simulated flows were compared to the observed flows at Burrows Well and a fourth order polynomial fitted to the data (see Illustration 4.2).

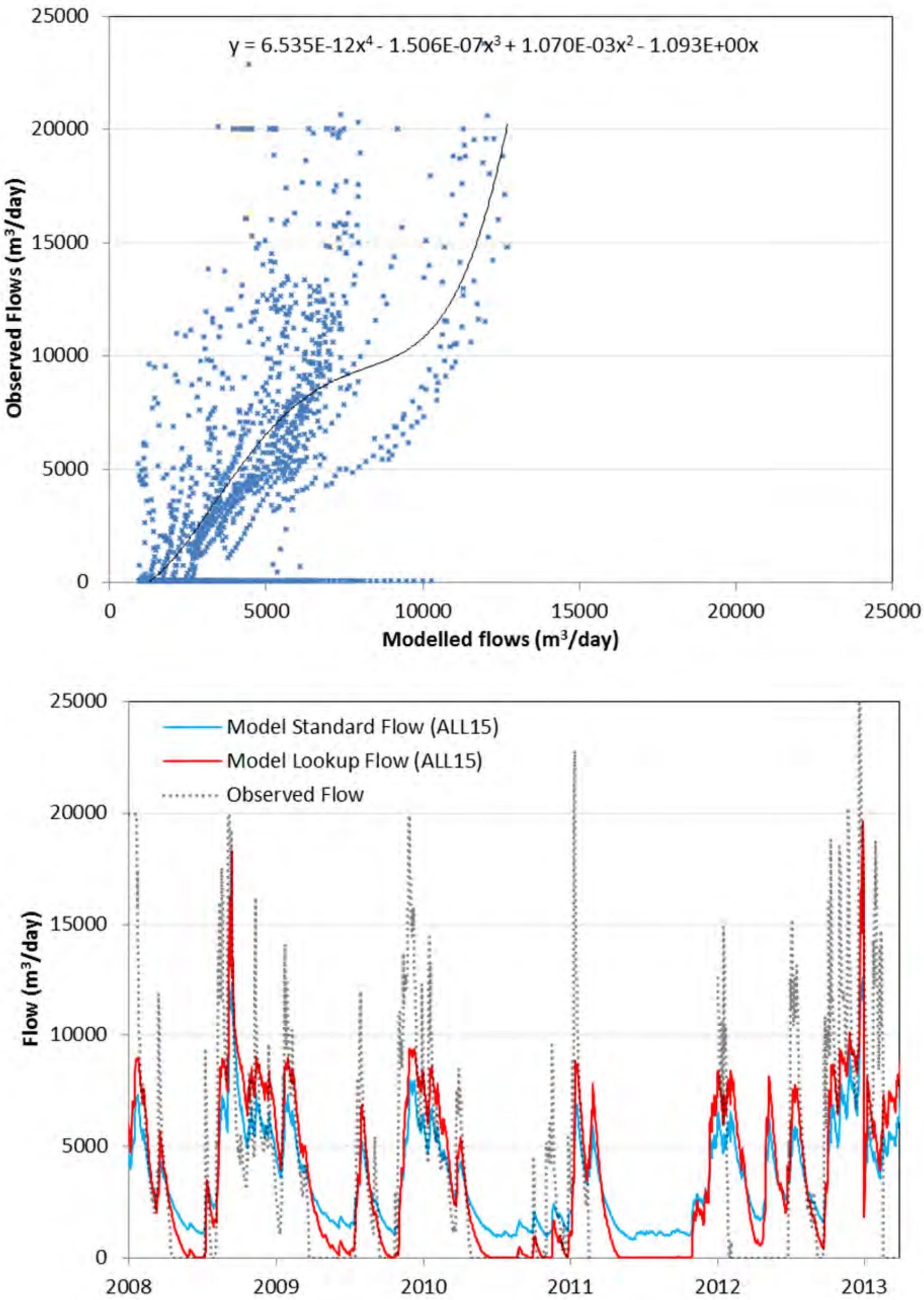


Illustration 4.2 Modelled vs Observed for Burrows Well flows lookup function

The polynomial then is used as a lookup function to transform the simulated flows at Burrows well under revised versions of the Baseline and ALL15 development runs into a data sequence that is more consistent to the observed values. That is, the model value (x) is replaced with the transformed value (y) used subsequently as the discharge at Burrow Well (note that the function is truncated where it crosses zero on the y-axis; modelled flows below 1300 m^3/day are transformed to ‘no flows’).

Although this potentially creates an overall imbalance in the model water balance (i.e. where water is added or subtracted according to the lookup function), the principle concern is with the relative changes in simulated water levels downstream in the Blown Sands at Merthyr Mawr. In this way an assessment can be made as to whether the relative changes between Baseline and Development runs using an improved representation of flows from Burrows Well are more or less than those simulated using the standard representation.

Whilst the results of the standard predictive run sensitivity analysis are presented in Appendix 7.4, it is more appropriate to discuss this specific issue here in terms of overall model credibility.

Illustration 4.3 shows the effect of transforming Burrows Well flows on the predicted change in water levels in the Blown Sand cells at Merthyr Mawr under the All15 development scenario (i.e. v. Baseline).

The average post development difference in water levels between the calibrated model and the sensitivity run with the Burrows Well function is set out in Table 4.3. This shows that using the Burrows Well flow function increases the simulated effect of the proposed development (i.e. All15 v. Baseline) by between 13 and 17%. This is considered to be small relative to the uncertainties in the whole assessment process and suggests that, whilst the calibration of flows at Burrows Well is not ideal, this is unlikely to affect the overall conclusions of the assessment. This constrained level of uncertainty has been taken forward into the overall assessment.

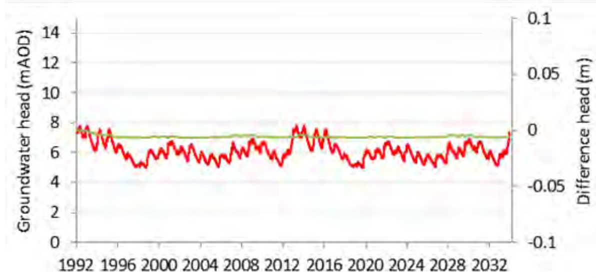
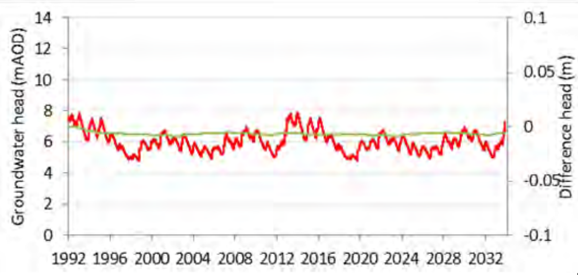
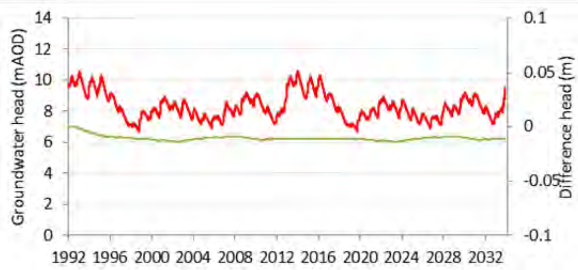
<table>
<tr><th></th><th>Calibrated Model</th><th>With Burrows Well Function</th></tr>
<tr><td>44</td><td>
</td><td>
</td></tr>
<tr><td>45</td><td>
</td><td>
</td></tr>
</table>

Illustration 4.3 Effect of using Burrows Well flow function on simulated post development change in water levels

Cell	Calibrated Model	With Burrows Well Function	% difference
44	-0.0058	-0.0068	17%
45	-0.0093	-0.0105	13%

Table 4.3 Model prediction runs

Run	Description	Run Type	Stage (year)	Development depth (mAOD)			Starting Heads	Disposal locations
				Cornelly	Grove	Gaens		
1	Baseline	Baseline		-3	no dewatering	no dewatering	1st Jan 2013 CA	Cornelly ⇔ Grove
2	CN15	Development	15	-30	no dewatering	no dewatering	1st Jan 2013 CA	Cornelly ⇔ Grove
3	CN42	Development	42	-75	no dewatering	no dewatering	1st Jan 2013 CA	Cornelly ⇔ Grove
4	GR15	Development	15	-3	-15	no dewatering	1st Jan 2013 CA	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting
5	GR42	Development	42	-3	-15	no dewatering	1st Jan 2013 CA	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting
6	GA15	Development	15	-3	no dewatering	0	1st Jan 2013 CA	Cornelly ⇔ Grove : Gaens ⇔NW
7	GA42	Development	42	-3	no dewatering	-20	1st Jan 2013 CA	Cornelly ⇔ Grove : Gaens ⇔NW
8	ALL15	Development	15	-30	-15	0	1st Jan 2013 CA	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
9	ALL42	Development	42	-75	-15	-20	1st Jan 2013 CA	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
10	Combined recovery	Recovery	-	-	-	-	1st Jan 2034 ALL42	-
11	SENS1	Sensitivity	-	-30	-15	0	1st Jan 2013 S1	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
12	SENS2	Sensitivity	-	-30	-15	0	1st Jan 2013 S2	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
13	SENS3	Sensitivity	-	-30	-15	0	1st Jan 2013 S3	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
14	SENS4	Sensitivity	-	-30	-15	0	1st Jan 2013 S4	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
15	SENS5	Sensitivity	-	-30	-15	0	1st Jan 2013 S5	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
16	SENS6	Sensitivity	-	-30	-15	0	1st Jan 2013 S6	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
17	SENS7	Sensitivity	-	-30	-15	0	1st Jan 2013 S7	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
18	SENS8	Sensitivity	-	-30	-15	0	1st Jan 2013 S8	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW
19	SENS9	Sensitivity	-	-30	-15	0	1st Jan 2013 S9	Cornelly ⇔ Pant Mawr : Grove ⇔Railway Cutting : Gaens ⇔NW

5 REFERENCES

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FIGURES

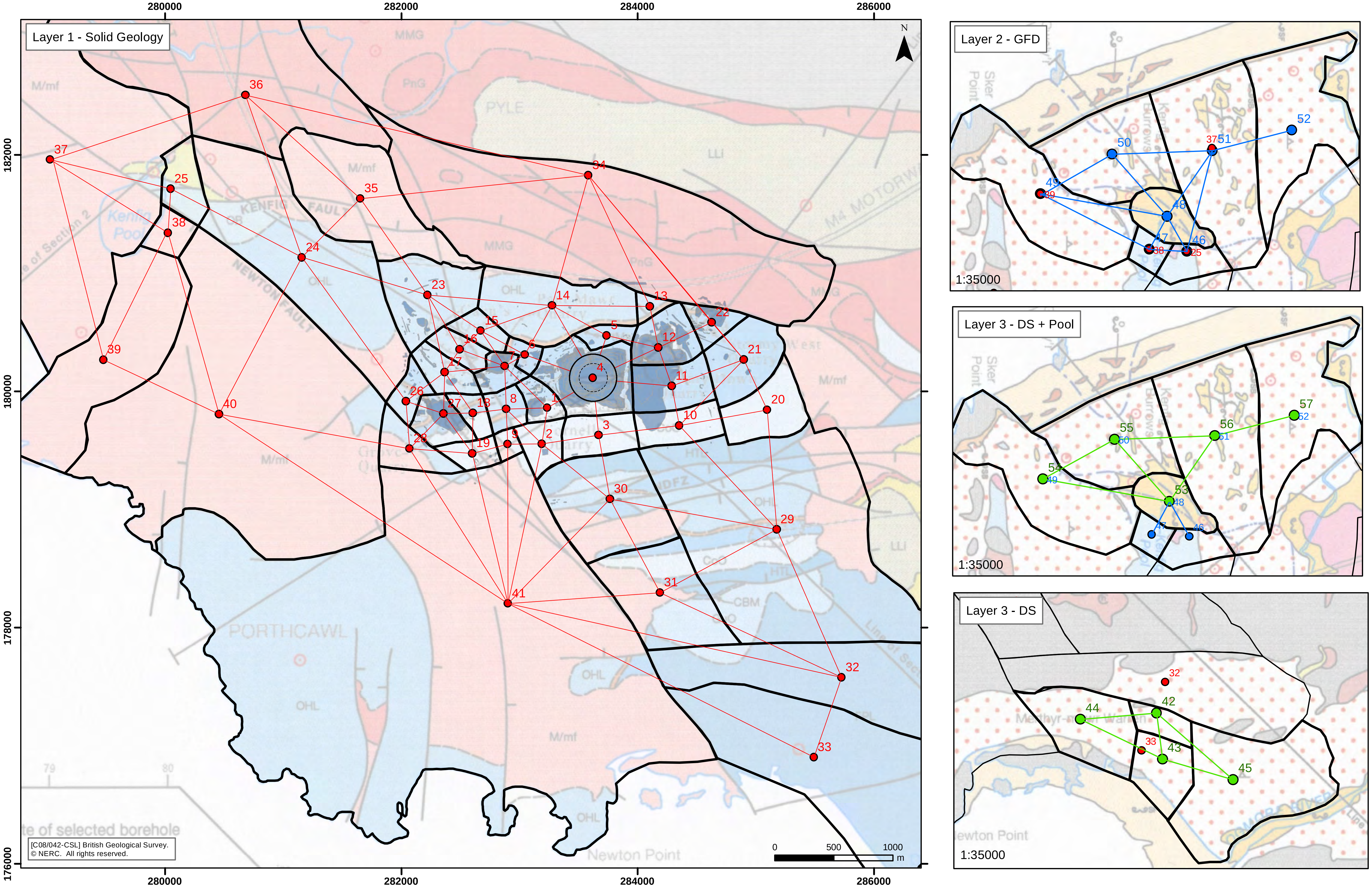

Figure 2.1
Model zones and connections

Date	Drawn
Jan 2014	SRA
Scale 1:30,000	Checked BCH
Original A3	Revision 1

File Reference
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esi Environment Specialists

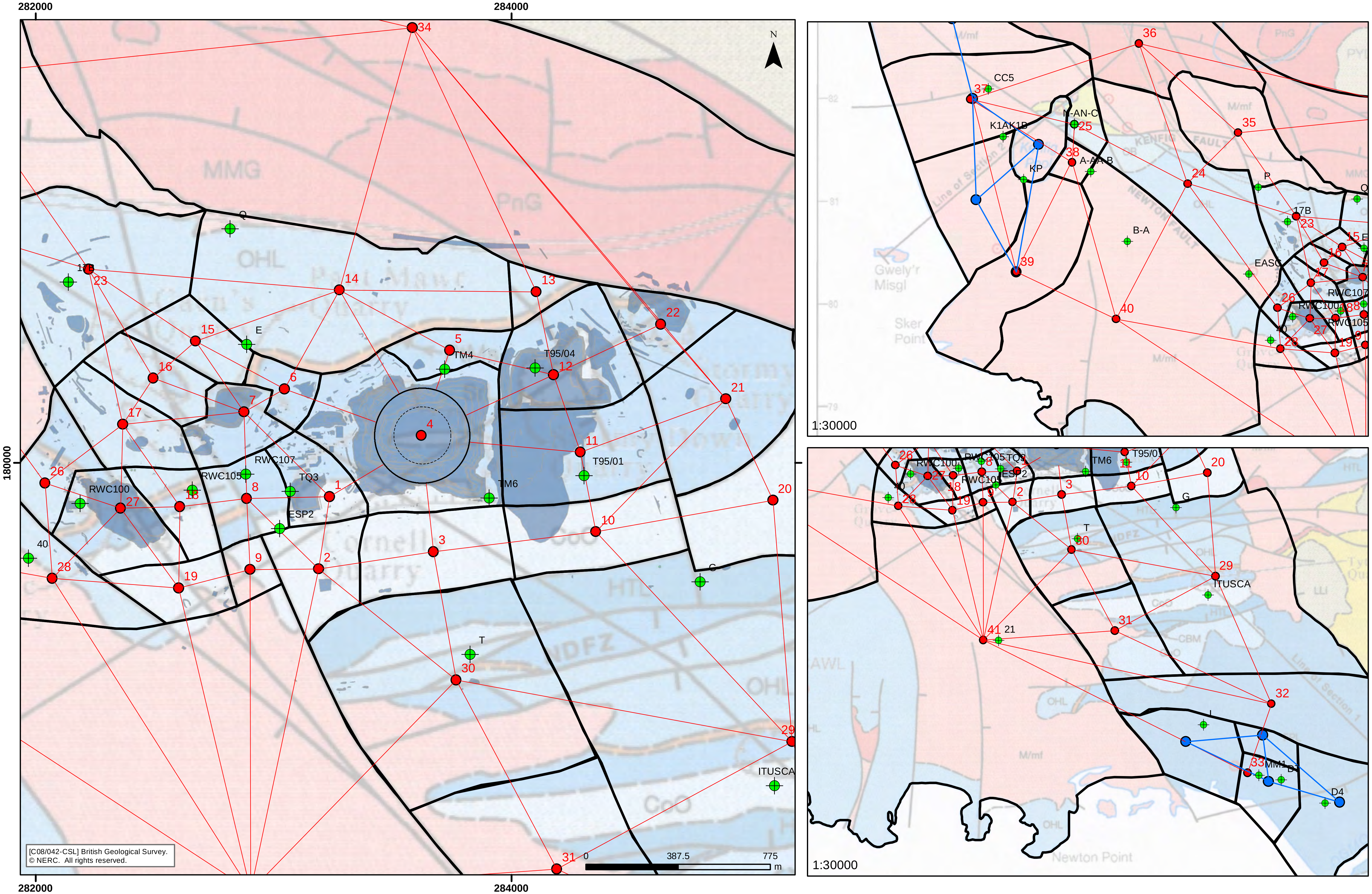

Figure 3.1
Locations of calibration boreholes

Date	Drawn
Jan 2014	SRA
Scale	Checked
1:15,000	BCH
Original	Revision
A3	1

File Reference
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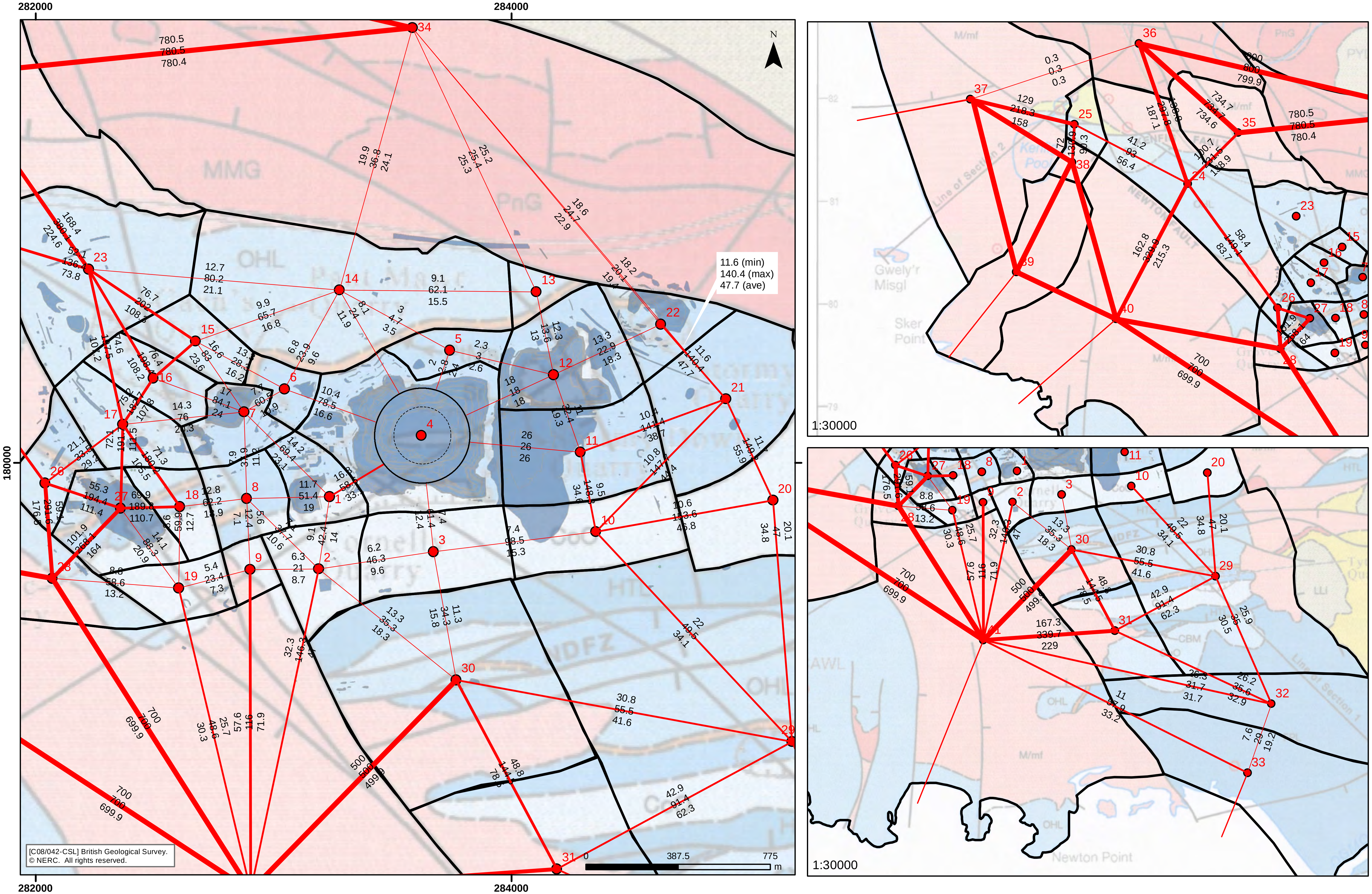

Figure 3.2
Solid geology calibrated transmissivity values

Date	Drawn
Jan 2014	SRA
Scale	Checked
1:15,000	BCH
Original	Revision
A3	1

File Reference
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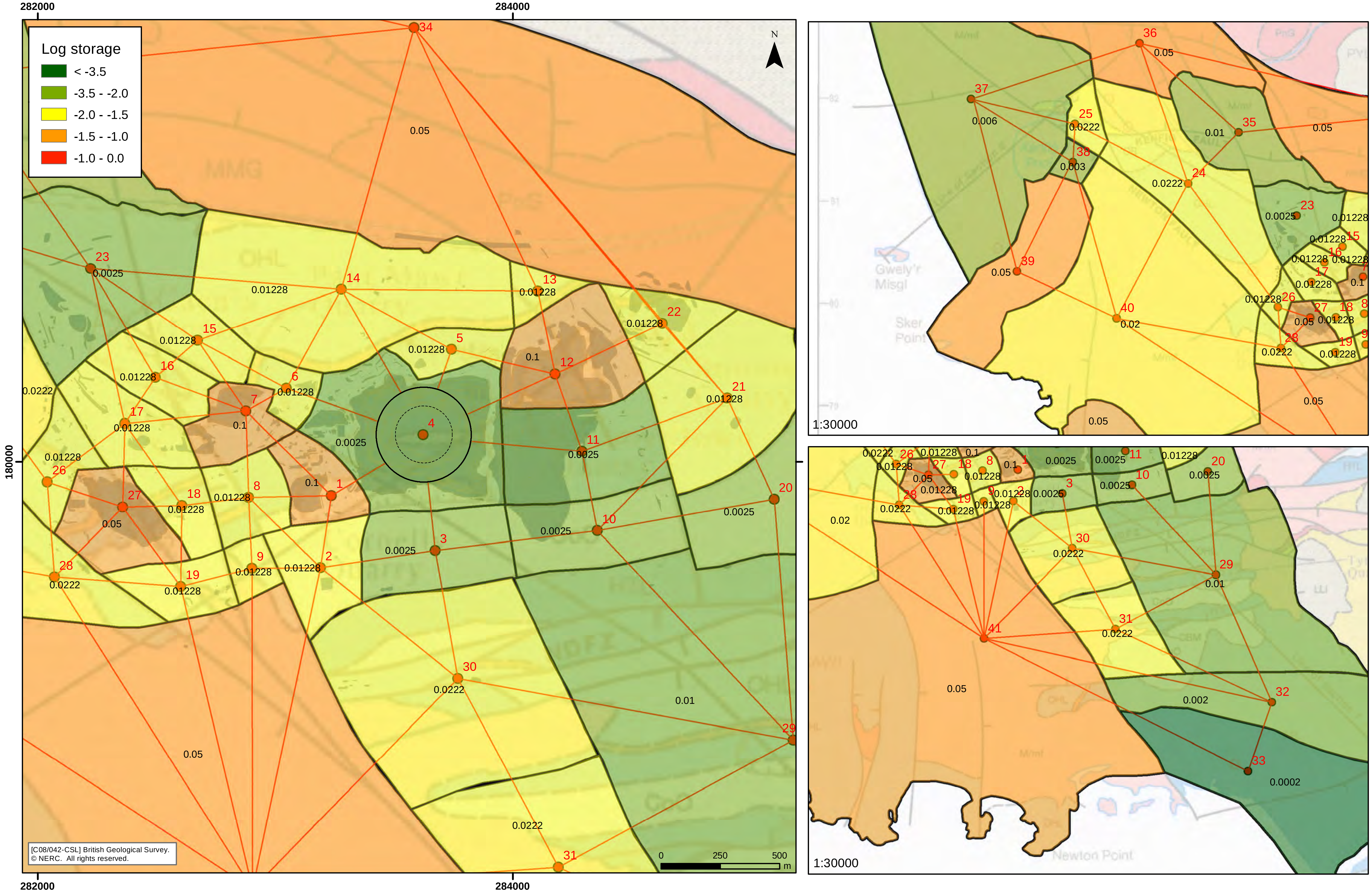

Figure 3.3
Solid geology calibrated storage values

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Jan 2014	SRA
Scale	Checked
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Original	Revision
A3	1

File Reference
O:\6227_Cornelly\reports\R17 EIA\Appendix 7.3 Groundwater Modelling Report\Figures\Figure 3.3 Calibration Solid Geology S.mxd

esi Environment Specialists

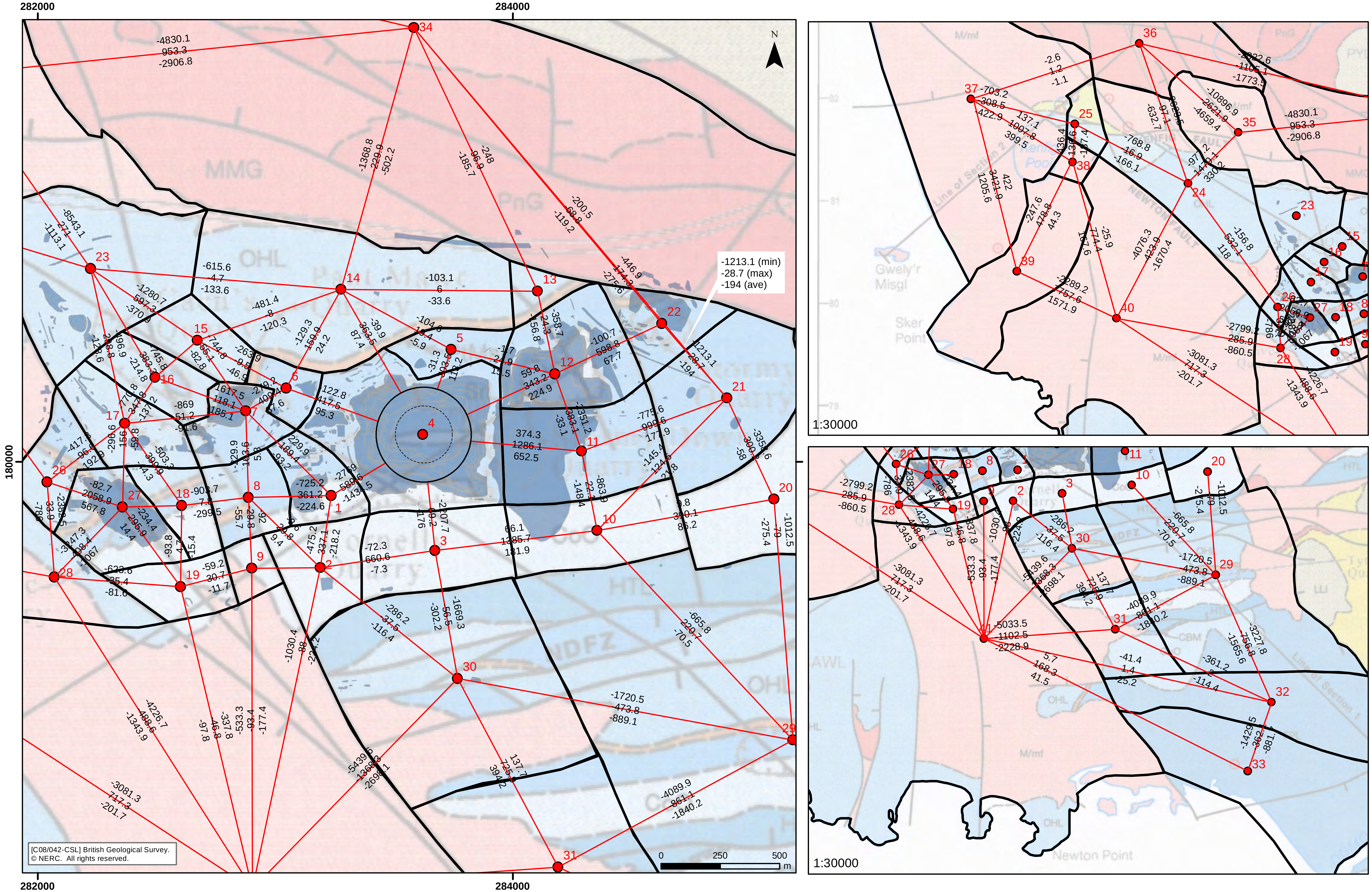

Figure 3.4
Solid geology lateral groundwater flows

Flows direction assumes Zone From < Zone To
+ve values indicate inflow
-ve values indicate outflow

Date	Drawn
Jan 2014	SRA
Scale 1:15,000	Checked BCH
Original A3	Revision 1

File Reference
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APPENDIX F

Summary of Hydrogeological ES for Cornelly Quarry (SLR, 2014)

Appendix F Summary of Results of Hydrogeological ES for Cornelly Quarry

F.1 Conceptual Model

A comprehensive, updated conceptual model is presented in Appendix 7.1 of the Environmental Statement for Cornelly Quarry (SLR, 2014) and summarised in this section.

The Cornelly Group of quarries work Carboniferous Limestone that forms part of a wider, inter-connected aquifer system extending over an area of around 25 km^2 (see Figure 6.1 of Appendix 7.1). This is bounded by the River Kenfig to the north, the River Ogmore to the south, by various faults to the north east and by the coast to the south and west.

The Carboniferous Limestone forms the main, karstic aquifer in this area but is overlain by permeable, layered and possibly karstic, Triassic strata to the west and south. The Blown Sands at Kenfig and Merthyr Mawr form minor aquifers that have a degree of connection with the underlying Carboniferous/Triassic aquifers.

Groundwater discharge from the limestone aquifer occurs as follows:

- Along the ~10 km of coastline that forms the western and southern boundaries of the area. This accounts for around 70% of the total discharge;
- At the large springs at New Mill Farm;
- Within the Blown Sand dunes at Kenfig and in Kenfig Pool;
- At the large spring at Burrows Well;
- Pumping from Cornelly Quarry (and occasionally from Grove and Gaens Quarries). This water is all re-circulated back into the limestone and is therefore not lost to the system.

The following sections describe the conceptual model of some of the key parts of this system in more detail.

<u>Cornelly Group of Quarries</u>

Over a period of ~30 years groundwater levels at Cornelly have been reduced by a total of around 60 m over an area of around 0.5 km^2. Average inflows to the quarry sump are only ~3,500 m^3/d and the off-site pumping rate is only around 2,000 m^3/d - equivalent to a catchment area of less than 1 km^2.

The low transmissivity of the aquifer in this area is due to a combination of stratigraphical, structural and erosion/dissolution processes.

The present phase of karst development/re-activation in the limestone at Cornelly extends down about 40 m from the surface. The dewatered saturated zone appears to be characterised by diffuse fracture flow rather than a karst conduit network. This suggests that there is a low probability of the further deepening of Cornelly quarry encountering significant zones of enhanced permeability at depth.

The extent of active karst in Gaens and Grove quarries is less clear as these quarries are smaller and have not been worked to such depths.

Groundwater gradients to the west of the Newton Fault are generally flatter than to the east, implying a much lower transmissivity in the latter area.

<u>New Mill Springs</u>

New Mill Springs form an important discharge point for the northern part of the Carboniferous Limestone/Triassic aquifer system. The total gain in the River Kenfig in this area is consistent with a catchment area of 8.8 km^2.

Kenfig Pool and Dunes

The groundwater system at Kenfig comprises three aquifers: the Blown Sand dunes, and the underlying glaciofluvial gravels and Carboniferous/Triassic aquifers.

The eastern boundary of the saturated Blown Sand aquifer follows the eastern boundary of Kenfig Pool northwards to the remains of Kenfig castle and south west out to Sker point. A laterally extensive low permeability estuarine clay layer below the sands limits the hydraulic connection between the sands and the underlying aquifers.

Groundwater flows from a groundwater high north west of Kenfig Pool westwards towards the coast, north to the River Kenfig and south east to Kenfig Pool. Groundwater level and hydrochemical data imply that recharge from rainfall over the site provides the great majority of flow in the system.

The underlying gravels form a minor, confined aquifer. Groundwater level trends are similar (albeit subdued) compared to the underlying Triassic strata suggesting a degree of connection. Fluctuations are much larger than within the Blown Sands and the hydraulic gradient is downwards except in very wet periods. This indicates that these two aquifers are not well connected. Comparison of gravels groundwater levels with Kenfig Pool levels implies that this aquifer system discharges towards the coast rather than upwards through the sands.

Merthyr Mawr

There are two distinct hydrogeological units at Merthyr Mawr – the Blown Sand superficial deposits at surface and the underlying Carboniferous Limestone. A degree of hydraulic separation between the two units is provided by a clay layer which appears to be present across the majority of the site and is typically more than 0.5 m thick.

A step in the underlying limestone separates the Blown Sand deposits into two topographic levels: an area at lower elevation, within which the dune slacks form, adjacent to the sea and an area at higher elevation further inland which is considered to be largely dry.

Limestone water levels are generally below those in the sand, however, due to a higher degree of fluctuation there are times when the limestone aquifer water levels are higher than the sand levels and the gradients are reversed. Burrows Well spring discharges during periods of high limestone groundwater level

In the area to the south of Burrows Well, water levels are affected by the discharge of limestone groundwater levels into the Blown sands which causes large areas to pond, possibly on a shallow clay layer in this area (SWS, 2010). When the spring stops flowing, these water levels drop rapidly by three or more metres (e.g. piezometer D7) i.e. the groundwater system in this area is not typical of dune slacks more generally.

There are three main inputs to the groundwater system in the sands: direct recharge, runoff from less permeable catchments to the north east and intermittent flow from the underlying Carboniferous Limestone that discharges at Burrows Well. Groundwater flow in the limestone and Blown Sand aquifer is southwards towards the sea.

Water Balance

The following conclusions regarding water balance have been drawn from the work carried out:

- Almost all of the flow in the Blown Sands at Kenfig is sourced from direct rainfall (2% from surface water inflow). This flow leaves the system by a mixture of groundwater flow and overland flow via the slacks with a very small component of downwards leakage into the underlying sands and gravels.
- New Mill Farm springs appears to account for all of the water recharging to the Carboniferous Limestone and Triassic marginal facies aquifers in the northern part of the study area.

- The diffuse nature of coastal outflows around Porthcawl mean that the water balance is not as good.
- 45% of the total inflow to the Blown Sand system comes from Burrows Well discharge with the remainder being sourced by direct recharge. The majority flows to the sea; around 14% leaks downwards to the underlying limestone.

F.2 Summary of Results of Impact Assessment

This section contains a summary of the results of the hydrogeological impact assessment for Cornelly Quarry (SLR, 2014 Chapter 7). This is provided to assist cross reference between the WMP and the ES. For further detail on the approach used etc., the original report should be used.

F.2.1 Approach

The assessment is based on the standard *source-pathway-receptor* approach and is sub-divided into a number of steps:

1. Identification of receptors
2. Identification of pathways
3. Quantification of effects
4. Assessment of significance/impact

A number of critical thresholds have been set to screen out those effects which may be significant from those that aren't:

- Licensed groundwater abstraction boreholes - predicted groundwater level reduction in excess of 0.5 m
- Shallow wells - predicted groundwater level reduction in excess of 0.25 m.
- Ponds (excluding Kenfig Pool and any dune slacks in Kenfig Pool and Dunes and Merthyr Mawr SAC) - predicted groundwater level reduction in excess of 0.1 m.
- Spring flows - derogation of flow in excess of 10% of mean long term flows.

Degree of impact is assessed through consideration of the degree of effect and the importance of the receptor as summarised in the table below:

		Receptor Value		
		Low	**Medium**	**High**
Degree of effect	**Negligible**	Negligible	Negligible	Negligible
	Low	Minor	Minor	Moderate
	Medium	Minor	Moderate	Major
	High	Moderate	Major	Major

For reporting purposes effects/impacts are presented in four separate categories A to D as shown in the following section.

F.3.2 Results

(A) General effects on groundwater levels and flows – this is taken to include the assessment of the potential impacts on the water resources of the Swansea Southern Carboniferous Limestone groundwater (Water Framework Directive) body;

Quarry development generally results in decreased groundwater levels in the immediate vicinity of the quarries but these effects dissipate quickly with distance from the quarry. Recovery results in temporary decreases away from the quarry as water fills storage within the quarry voids. In some areas recovered levels are slightly higher and in other areas they are slightly lower due to the removal of the effects of quarry dewatering discharge.

Impacts are **Negligible** for individual development, combined development, and recovery conditions

(B) Potential effects on water levels in the dune sands at Kenfig Pool and Dunes SSSI and the Merthyr Mawr SSSI

Water levels rise slightly at Kenfig in the Cornelly-only development scenario but fall when all quarries are combined and during recovery. Stabilised recovered levels remain lower than current. The largest change in water levels at Kenfig is seen during recovery with a temporary drop of up 12 cm in the dunes to the east of Kenfig Pool. Planned Mitigation Measures reduce this below the 10 cm critical threshold. Changes in other dune cells and for other scenarios are not more than 1 cm. Hydrogeological impact is **Negligible**.

Water levels at Merthyr Mawr decline under all development scenarios and during the initial stages of recovery. Stabilised recovered levels and flows remain higher than current. The largest changes in level and flow at Merthyr Mawr are seen during recovery. Representative Blown Sand aquifer cells at Merthyr Mawr show no more than 3.5 cm reduction under all scenarios. Flows at Burrows Well do not exceed 5% peak reduction under all scenarios. Hydrogeological impact is **Negligible**.

(C) Potential effects on water levels and flows at other receptors

The largest changes in level and flows are seen during recovery.

Drawdowns in excess of the critical threshold are seen at:

- Ty Tanglwyst Farm pond (Loc. 17)
- Ty Tanglwyst Farm well (Loc. 17a)
- Ty Talbot Farm, Nottage (Loc. 18b)
- Wilderness Pond (Loc. 20)
- The well at White Wheat (Loc. 21)
- Pwll y Waun pond (Loc. 23)
- The well at Home Wood (Loc. 33)
- The pond at location 34 (Loc. 34)
- Royal Porthcawl Golf Club well (Loc. 36A & 36B)
- Grove Golf Club well (Loc. 40)
- Tynycaeau (Loc. 61)
- Pyle & Kenfig Golf Course (Loc. 65)

Of these, hydrogeological conditions mean that only Grove Golf club has **Moderate adverse** impact with the remainder considered **Minor adverse**.

Effects at springs vary depending on location and scenario. At New Mill Farm springs the greatest reductions in flow are seen during recovery. Short term flows initially exceed 10% reduction but flows increase over the recovery period. Impacts at springs are either **Negligible** or **Minor adverse** under all scenarios.

(D) Other potential effects

There is a relative increase in flows toward Cornelly Quarry from Stormy West landfill under all scenarios but the magnitude of flows is small. At Tythegston flows are always away from the quarries.

There are no ground stability effects.

Flows toward the coast are most reduced under in the recovery run where a maximum reduction of just under 9% is predicted.

APPENDIX G

Outline Engineering Measures to Control any Sudden Inflow of Water to the Quarry

19 March 2015

Reference: 14-143.102A.V1
Prepared by Dr M Preene

TECHNICAL NOTE
CORNELLY QUARRY – REVIEW OF GROUNDWATER CONTROL OPTIONS

Preene Groundwater Consulting Limited (PGC) has been instructed by ESI to summarize the options for controlling groundwater inflows in the event of encountering a fissure at depth. This Technical Note summarises this study.

1. The Proposed Works

Cornelly Quarry ('the Quarry') is an existing hard rock quarry exploiting the Carboniferous Limestone. The base of the Quarry is currently at approximately -3 mOD (approximately 100 m below surface), and is to be deepened in stages to -15 mOD, -30 mOD and -75 mOD. The Quarry currently requires dewatering by groundwater pumping from an in-pit sump, and this requirement is expected to increase as the quarry is deepened.

2. Hydrogeological Setting

The Quarry is sunk into the Carboniferous Limestone, the upper horizons of which are affected by paleokarst features of enhanced permeability, predominantly extending down to 40 m below surface. The description of the paleokarst features indicate that they may comprise dilated joints, breccia bodies or irregular pipes and voids. The paleokarst features are described as typically being filled with sediments of low permeability silts and clays. It is indicated that the proposed quarry development will be below the paleokarst zone, and the probability of encountering a significant permeable feature is low. Nevertheless, the Quarry requires a groundwater control contingency plan for such an event.

Predicted water inflow rates to the developed Quarry are indicated to be of the order of 3,000 to 4,000 m^3/d (35 to 46 l/s) with 50 to 60 % of this pumped off-site and the remainder re-circulated in other parts of the Quarry pit.

3. Groundwater Control Options

It is likely that a discrete permeable feature will be encountered in one of two ways. It may be exposed in the newly blasted face as the quarry is extended horizontally at a given level. Effectively, the Quarry would work laterally into the feature, in which case the flow from the permeable feature will probably be easy to identify quickly. Alternatively, the permeable feature may be encountered in the floor of the zone where the first deepening of a new stage of the Quarry is made. In these circumstances the Quarry will work down onto the feature, and while increased groundwater inflows will be observed, it may not immediately be obvious that a discrete permeable feature has been encountered. In either case, it is clear that all groundwater control options (including those based on grouting) will require some groundwater pumping, at least as temporary measure.

Groundwater control options at the Quarry fall into three main types:

1. *Accept the water into the Quarry pit and remove by in-pit pumping*. Conceptually this is the simplest solution, and simply involves allowing the water to flow from the feature, and directing it by drainage channels to a local sump from where it is pumped away. This appears feasible in practice because the current inflows are not very large, and

because further water entry into the pit is unlikely to cause geotechnical problems. The negative aspects of this approach are that the water disposal route has to accept significantly increased flow rates, and the larger groundwater inflows may cause greater external hydrogeological impacts.

2. *Intercept the water prior to entering the pit*. In theory, if the orientation and extent is known for a permeable feature exposed in the Quarry it may be possible to drill into the feature before it enters the pit and attempt to seal it with grout. However, in reality the uncertainties and access problems in a developing quarry rule out this option.
3. *Blocking of pathways to prevent water from entering the pit.* Where the feature is exposed in the Quarry, measures can be taken to seal or block the feature and exclude the water from the pit. The technical challenges are that any seal must be able to hold back significant groundwater pressure, and must be extensive enough to prevent water 'short-circuiting' around the seal and emerging nearby in the pit. A practical challenge is to locate the seal where it will survive for some time, and not quickly be destroyed by further blasting and pit expansion.

4. Preferred Groundwater Control Option

The preferred groundwater control solution to deal with a discrete permeable feature is to pump the groundwater inflow, on a temporary basis, and then, when pit geometry allows, seal the feature to exclude the groundwater. Outline stages of work are:

1. When a permeable feature is encountered, deploy temporary sump pumps to handle the inflow. Water to be pumped through a V-notch weir tank and flow rate measured daily during the works to determine if flow rate is constant or increasing/decreasing. Feature to be inspected to assess type, orientation, effective opening, etc.
2. Assess geometry of feature to determine where it will intercept a pit face or floor that will not be affected by blasting or pit development. Prepare a plan to seal the feature at that location (see outline steps below).
3. At the seal location, clean out as much sediment from the feature as is safely accessible (e.g. by scouring with jetting lance or narrow excavator bucket). Set minimum of two steel relief pipes in the feature, protruding into the Quarry void. Ideally the relief pipes should be 150 mm diameter if the feature is large enough to accommodate them. Relief pipes to terminate in a valve and flange.
4. Seal around the relief pipes using aquareactive polyurethane grout. This material reacts with the water to form a foamed void filler to seal around the pipes. Water will continue to flow from the feature through the relief pipes, so the grout is not subject to high water pressures.
5. Construct a reinforced concrete headwall across the exposed feature to give structural support to the relief pipes. The headwall will need to extend sideways out to sound rock, and may need to the bolted to the rock face. During construction water is allowed to flow through the relief pipes.
6. Once the concrete headwall is cured the relief pipes are closed off by the valves. A pressure sensor should be fitted to one of the relief pipes and the rise in groundwater pressures monitored following closing of the valves. An inspection should be made of the rock around the headwall to identify any zones where water is leaking, and if necessary these can be sealed with polyurethane grout.
7. Once the feature is sealed at the headwall, it can either be left full of water, or it can be backfilled with a cement-based void filling grout by pressure grouting through the relief well valves, with lower volume secondary injection of polyurethane grout if required.