

Vaynor Quarry ROMP: Supporting Groundwater Flow Modelling Report





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1 Introduction

1.1 Context and Purpose

This report has been prepared by Stantec UK Ltd (Stantec) on behalf of Hanson UK Ltd (Hanson) in support of the Review of Old Mineral Permissions (ROMP) application for Vaynor Quarry (the Site). Groundwater will be intercepted by limestone extraction activities in the quarry void and will be passively dewatered through drainage to ponds in hydraulic continuity with the limestone aquifer. Further details of the proposed activity are provided in Stantec (2020). Soakage from the ponds would ensure maintenance of spring flows in the Cwm Taf Fechan Special Area of Conservation (SAC).

The purpose of this report is to present the construction of and results from a groundwater flow model built to support the Hydrogeological Impact Assessment (HIA) prepared by Stantec (Stantec, 2020). The modelling has been designed to inform the pond design and to demonstrate whether there would be sufficient infiltration to mitigate potential impacts of further quarry development on springs in the Cwm Taf Fechan SAC.

The results have been used to inform the HIA, and this report should be read in conjunction with the HIA prepared by Stantec (2020).

1.2 Report Outline

This report contains:

- a description of modelling undertaken, calibration and model results for current conditions (Section 2);
- predictive model results to estimate future conditions at the maximum extent of quarrying and to inform pond design (Section 3); and
- a summary of key conclusions (Section 4).

2 Groundwater Flow Modelling

2.1 Approach

A steady state groundwater flow model has been constructed and calibrated using available groundwater level data to represent existing conditions, which include an element of passive dewatering. A predictive model has then been built to predict groundwater heads at the final extent of the quarry development. The construction of and results from these models are described in Sections 2 and 3 respectively.

2.2 Model Construction

2.2.1 Modelling software and solver

The modelling code used in the assessment is MODFLOW-USG (Panday, et al., 2017). MODFLOW-USG uses a finite difference approach to solve the groundwater flow equations and allows local refinement of the model grid to improve the resolution of predictions at the Site. The model has been built and run with the Graphical User Interface (GUI) Groundwater Vistas, Version 7.24.

2.2.2 Model grid

The grid extends 4.9 km north and 4.5 km east of an origin located at NGR SO017071 and the parent grid cell size is 50 x 50 m. To better constrain drawdown impacts from passive dewatering, for this work the grid was further locally refined to 10 x 10 m across 2.1 km² covering the Site and immediate surrounding area using a rectangular nested grid and the functionality of MODFLOW-USG (see Figure 2.1 to Figure 2.4). This localised refinement allows for more accurate representation of the quarry void, adjacent features, and the spread of drawdown. The parent grid is composed of 90 rows and 90 columns.

2.2.3 Model layers

The model is comprised of four layers. Each layer represents a different bedrock geology as follows:

- Layer 1: Strata overlying the Dowlais Limestone Formation, including:
 - Oxwich Head Limestone Formation;
 - Twrch Sandstone Formation;
 - Bishopton Mudstone Formation; and
 - Superficial strata.
- Layer 2: Dowlais Limestone Formation;
- Layer 3: Llanelly Formation; and
- Layer 4 Abercriban Oolite Subgroup.

Most of the strata overlying the Dowlais Limestone crop out away from the Site and are hence unlikely to influence hydrogeological conditions at the Site itself. Therefore, for simplicity, these have been grouped together in one layer. The influence of units which crop out on recharge is considered in Section 2.2.8. The base of the model is the contact between the Abercriban Oolite Subgroup and the Cwmyniscoy Mudstone Formation. The Cwmyniscoy Mudstone Formation is understood to behave as an aquitard and therefore forms the base of the limestone aquifer unit in this area.

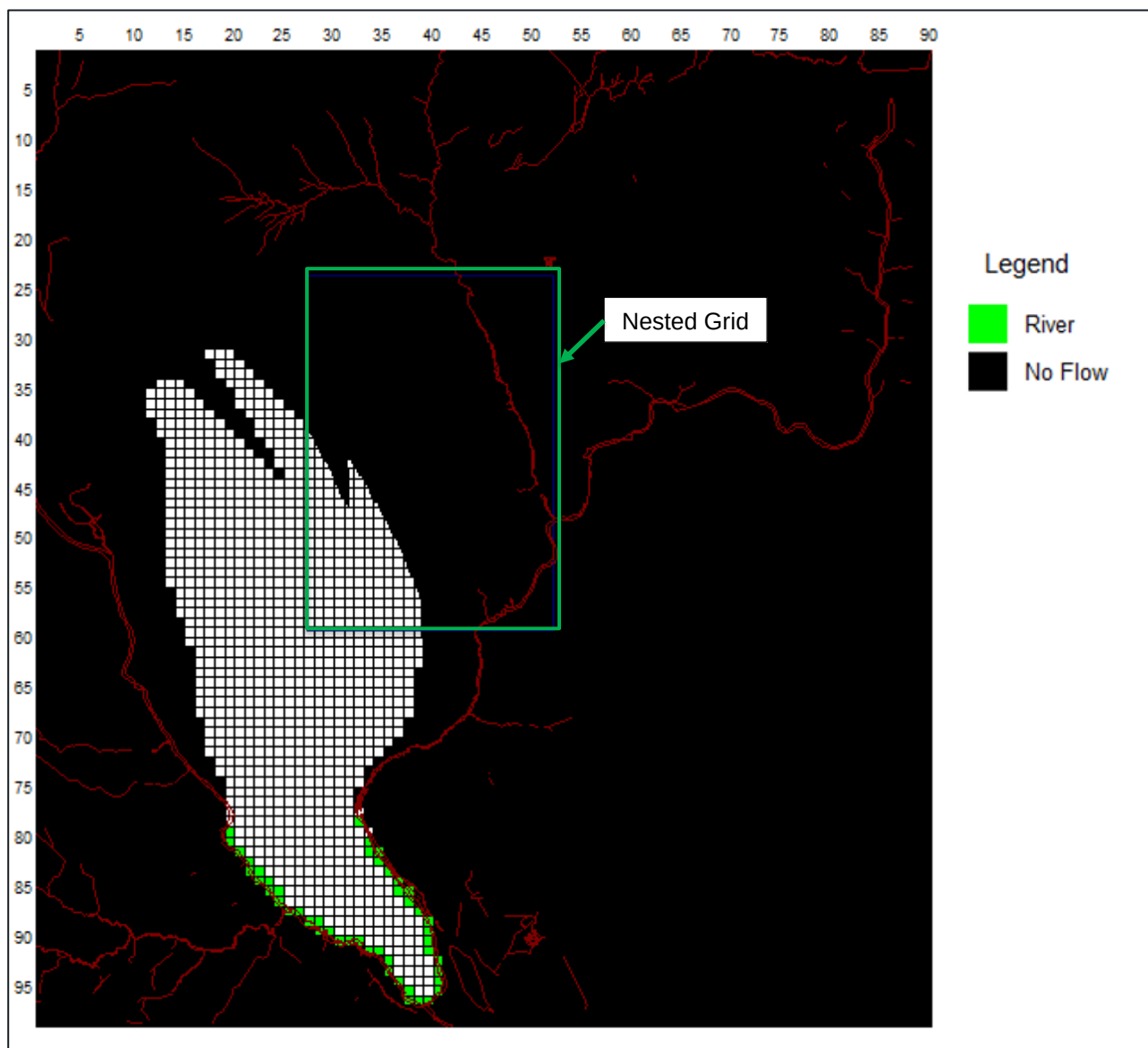
Figure 2.1 Model extent, nested grid area and model boundary conditions – Layer 1

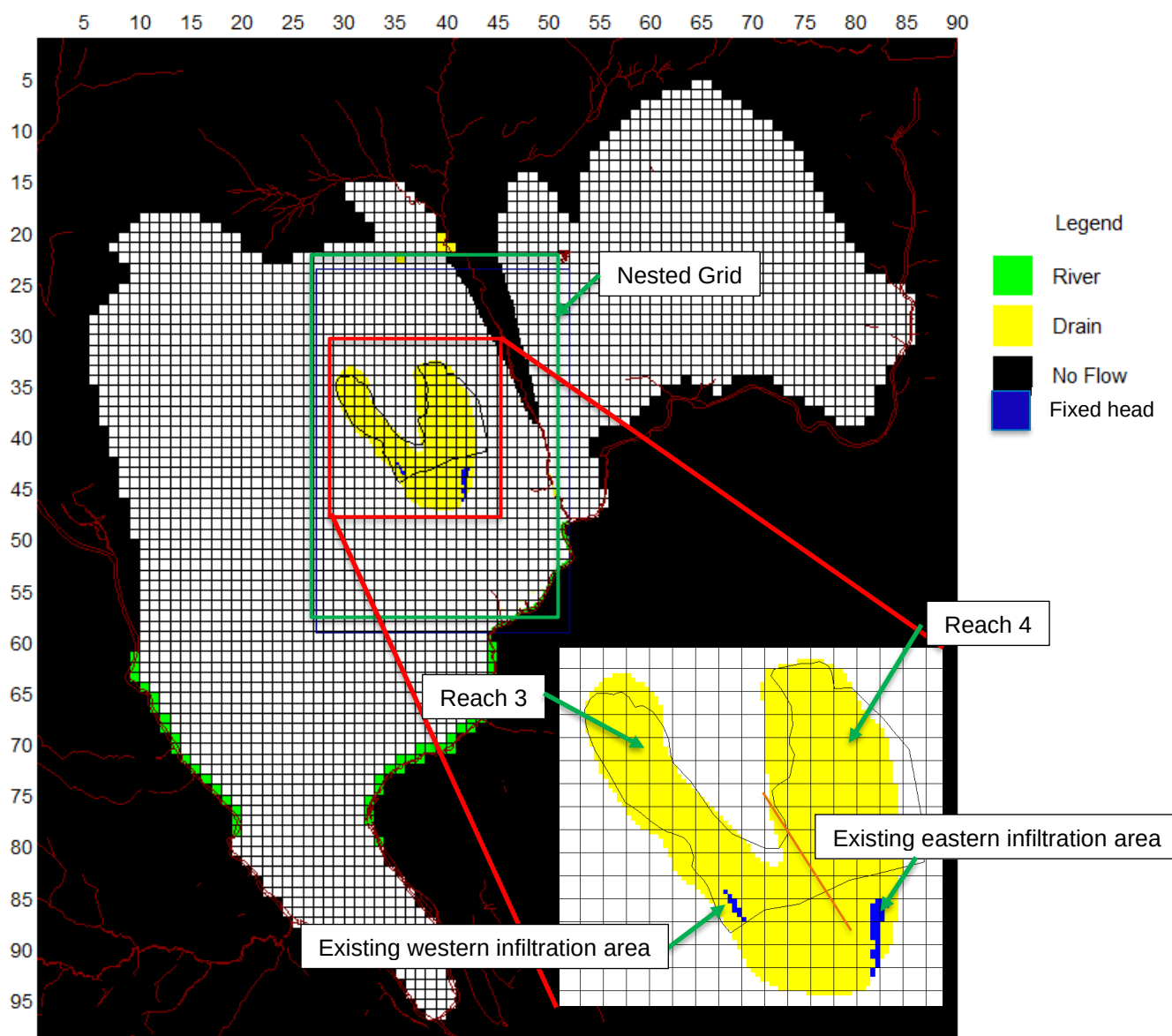
Figure 2.2 Model extent, nested grid area and model boundary conditions – Layer 2

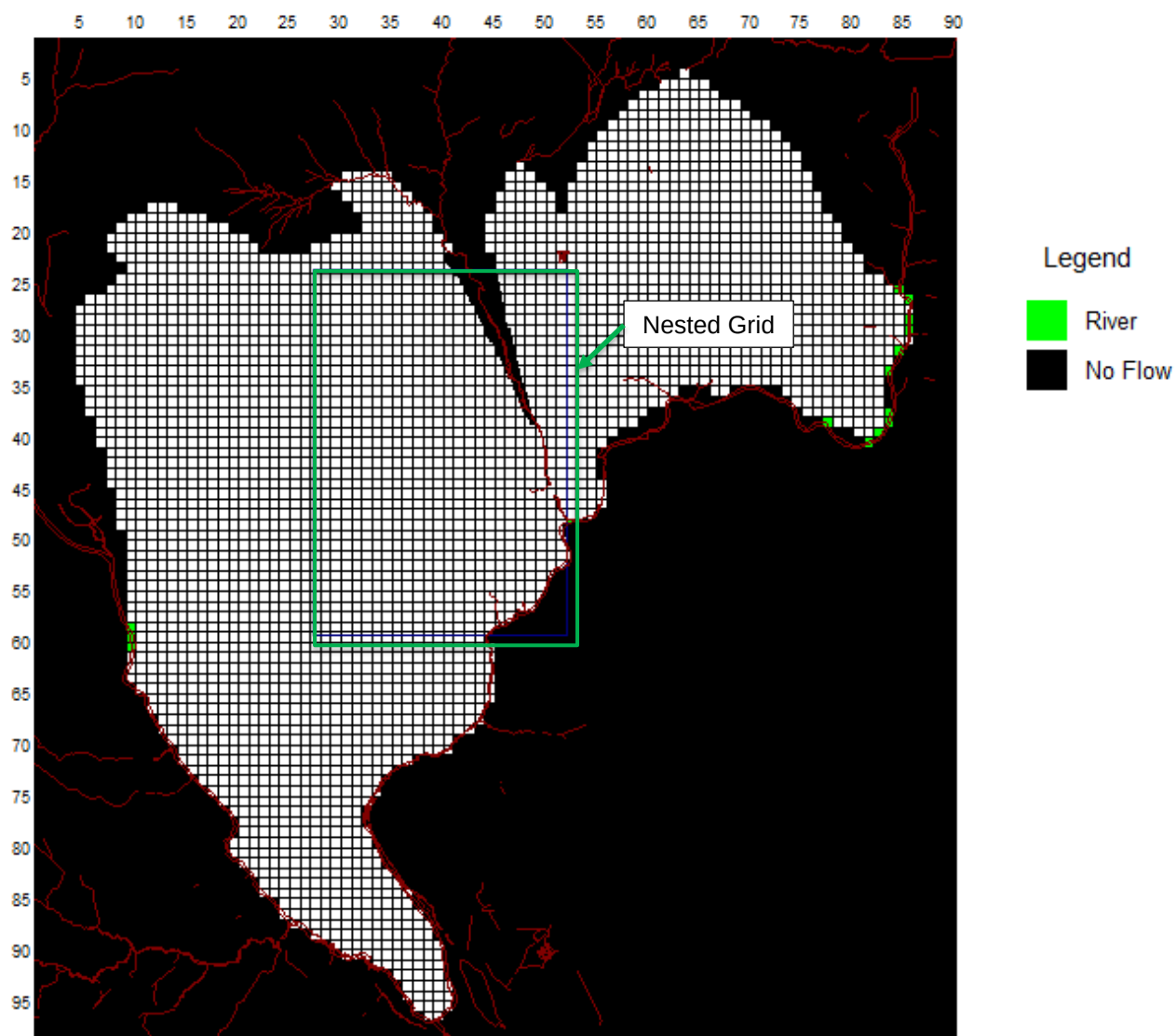
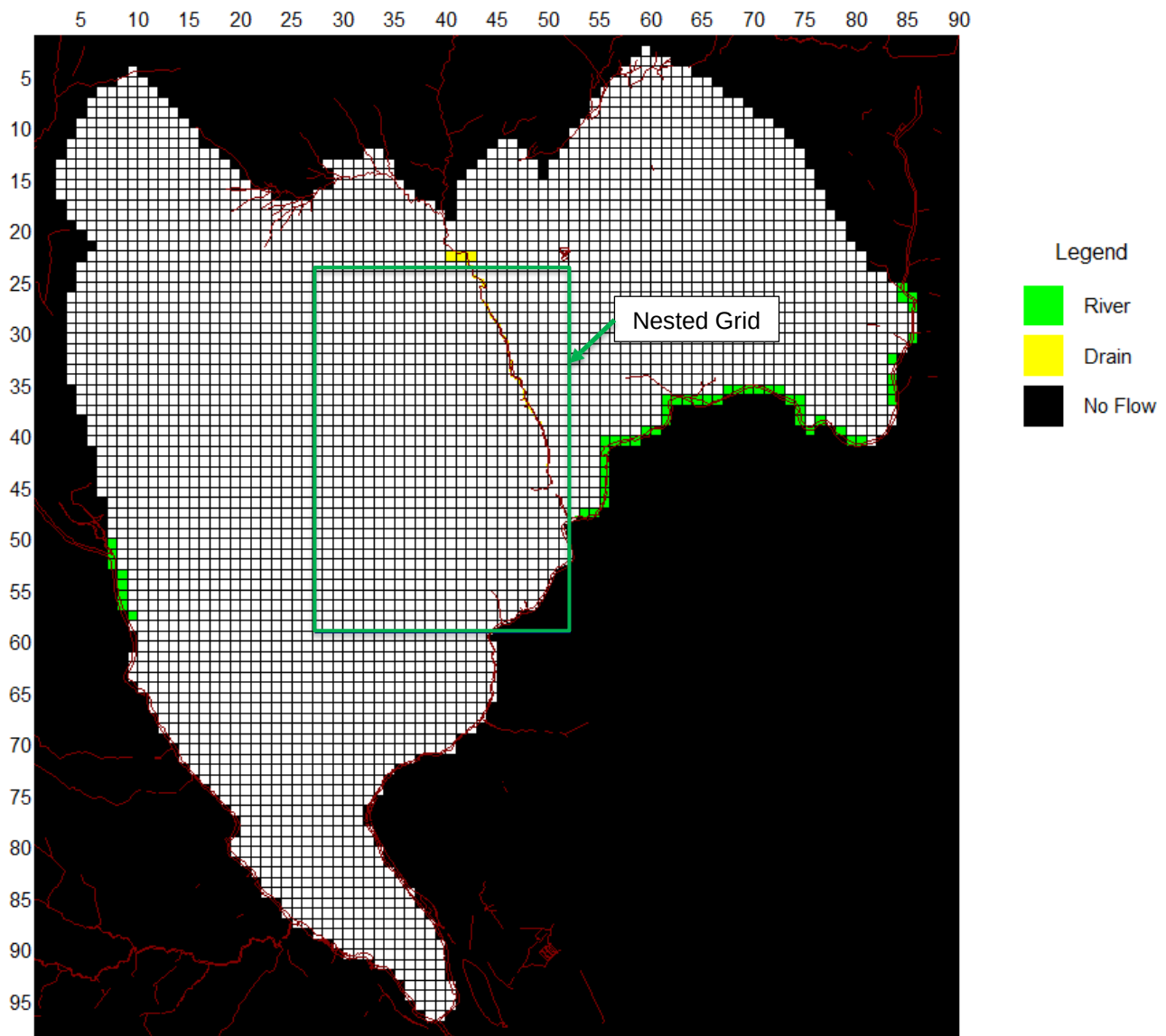
Figure 2.3 Model extent, nested grid area and model boundary conditions – Layer 3

Figure 2.4 Model extent, nested grid area and model boundary conditions – Layer 4

A summary of the derivation of each of the five model surfaces (tops of layers 1 to 4 and base of layer 4) is provided in Table 2.1. Stantec (2020) provides details of a Leapfrog model that was constructed using available borehole logs from Hanson, and logs and maps from the British Geological Survey (BGS). This model focuses primarily on the Site itself. Where available, the contact surface from the Leapfrog model has been used to derive the model surfaces. Elsewhere, gaps were filled in either by assuming a constant thickness based on borehole records from the Site or by using a constant dip based on Leapfrog modelling results. Details are provided in Table 2.1.

Where a unit is absent (i.e. where units that underlie the modelled layer crop out), layer thickness was set at a default value of 0.1 m and the cell was set as inactive (i.e. no flow). For example, for Layer 2, which represents the Dowlais Limestone Formation, areas where the older Llanelly Formation and Abercriban Oolite Subgroup crop out are set as inactive. No flow zones are shown in black on Figure 2.1 to Figure 2.4. The top surface of Layer 1 (top layer) is shown on Figure 2.5 and the bottom surfaces of Layers 1 to 4 are shown on Figure 2.6 to Figure 2.9.

The top layer is defined as an unconfined layer (LAYCON = 1). The underlying layers are defined as unconfined (transmissivity varies) (LAYCON = 3).

Table 2.1 Derivation of model surfaces

Layer	Top/Bottom	Represents	Data source(s)
Layer 1	Top	Surface topography	LiDAR data
Layer 2	Top	Upper surface of the Dowlais Limestone Formation	- LiDAR data - Contact between Dowlais Limestone Formation and overlying strata from Leapfrog model - Estimates of upper Dowlais Limestone Formation contact from BGS borehole logs and based on an assumed dip
Layer 3	Top	Contact between Dowlais Limestone Formation and Llanelly Formation	- LiDAR data - Contact between Dowlais Limestone Formation and Llanelly Formation from Leapfrog model - Estimates of contact between Dowlais Limestone Formation and Llanelly Formation based on an assumed dip
Layer 4	Top	Contact between Abercriban Oolite Subgroup and Llanelly Formation	- LiDAR data - Contact between Abercriban Oolite Subgroup and Llanelly Formation from Leapfrog model - Estimates of contact between Abercriban Oolite Subgroup and Llanelly Formation based on Llanelly stratum thickness of 5 m
	Bottom	Contact between Abercriban Oolite Subgroup and Cwmyniscoy Mudstone Formation	- LiDAR data - Contact between Abercriban Oolite Subgroup and Cwmyniscoy Mudstone Formation from Leapfrog model - Estimates of contact between Abercriban Oolite Subgroup and Cwmyniscoy Mudstone Formation based on Abercriban stratum thickness of 20 m

Figure 2.5 Top elevation Layer 1

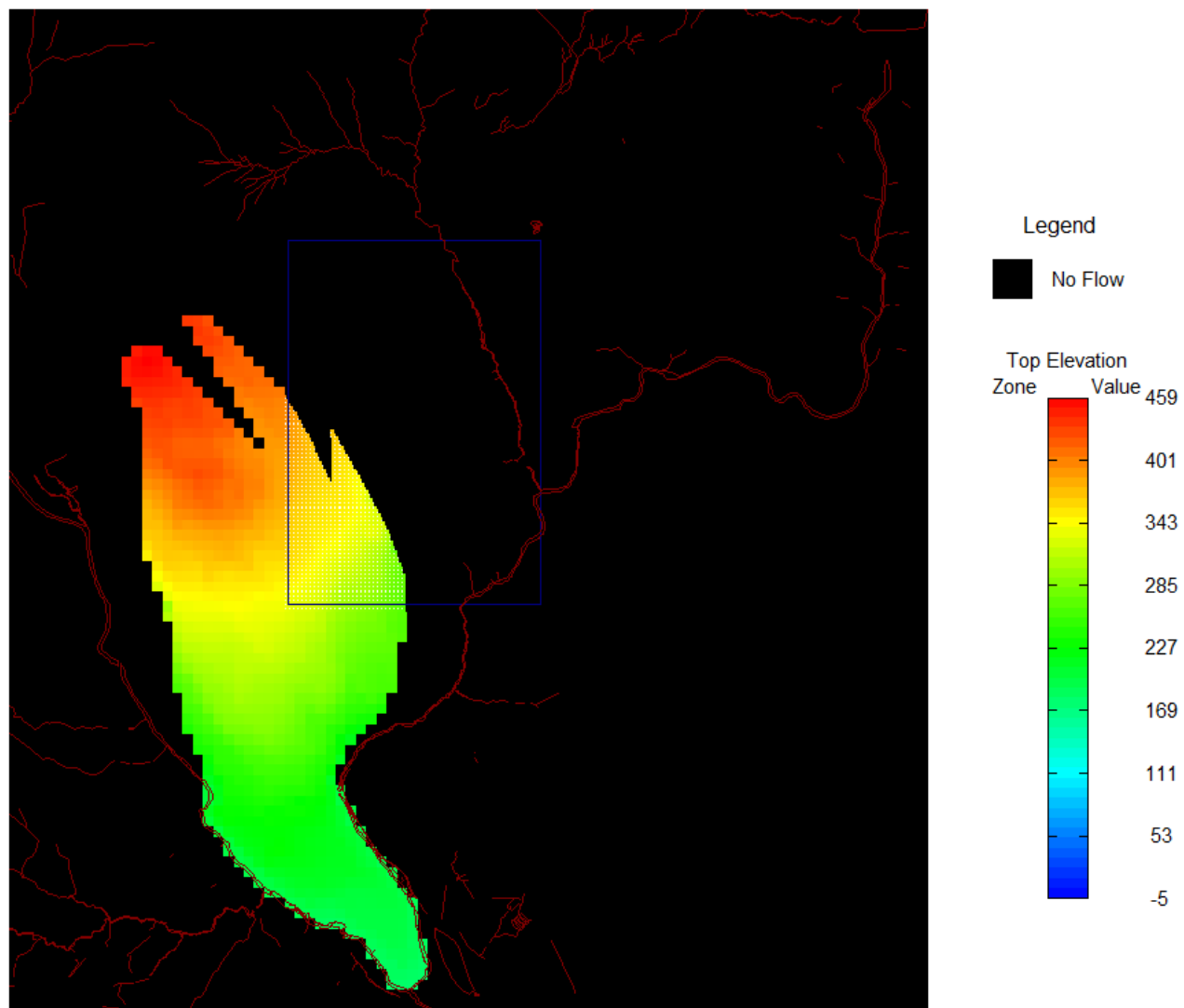


Figure 2.6 Bottom elevation Layer 1

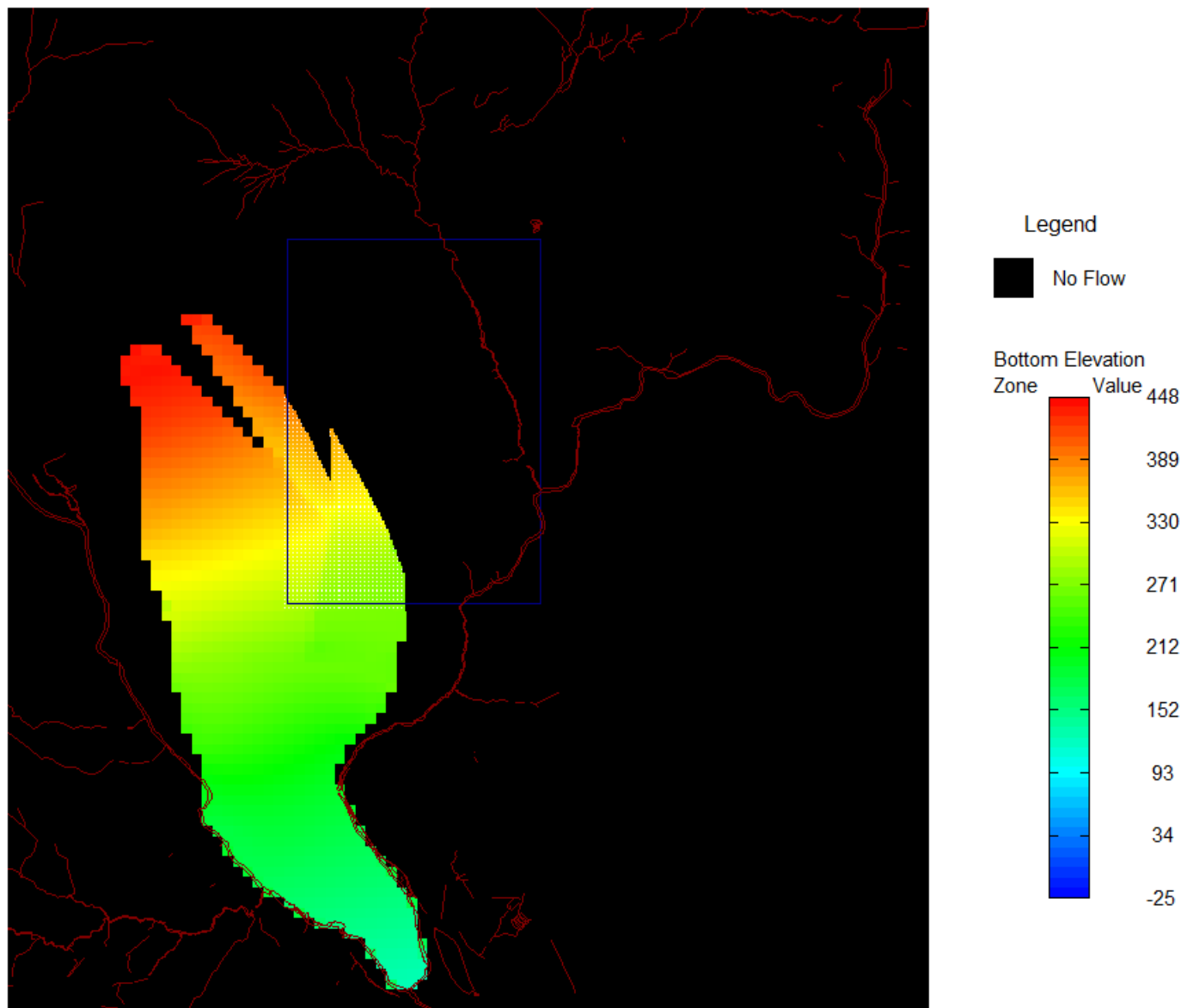


Figure 2.7 Bottom elevation Layer 2

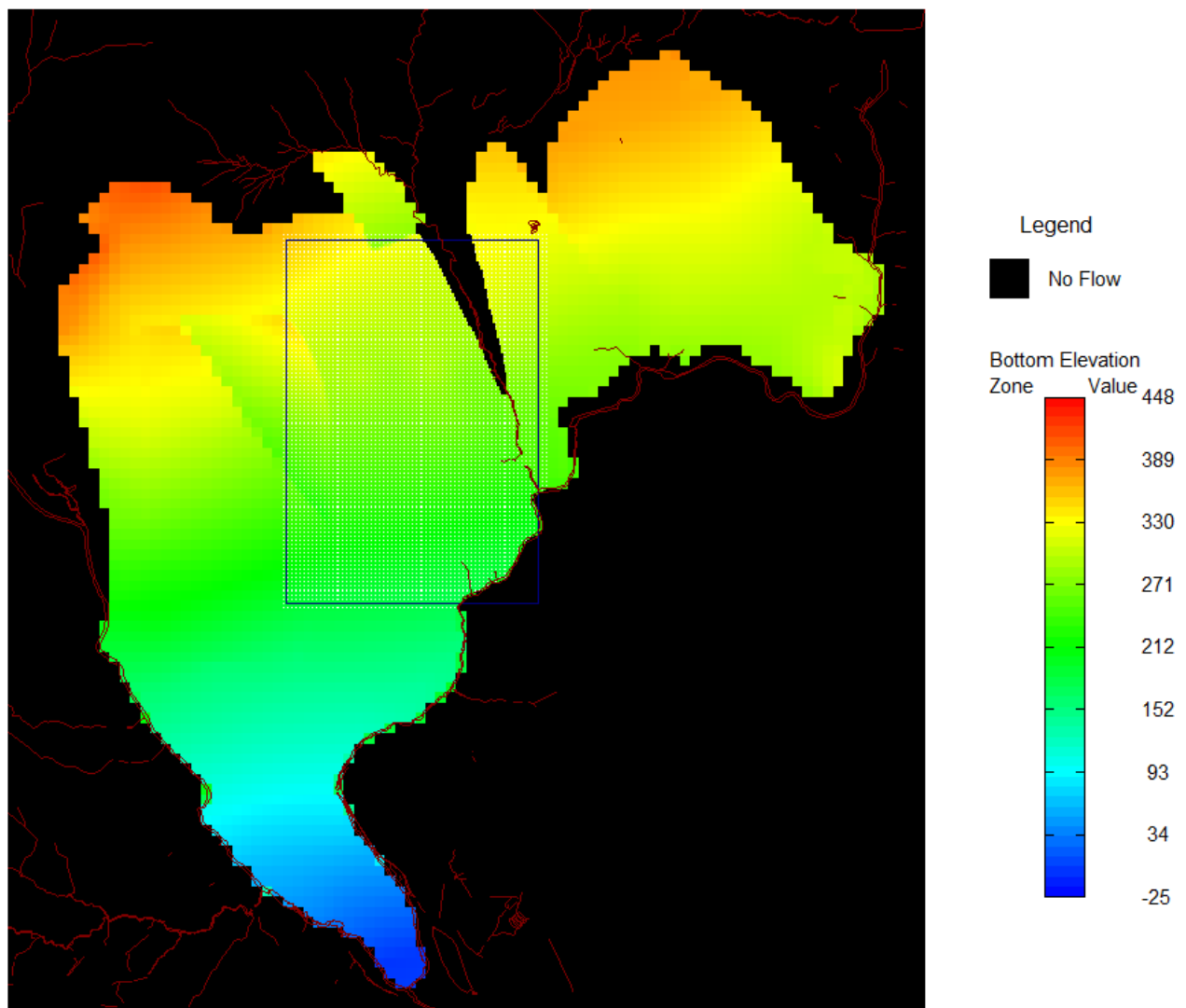


Figure 2.8 Bottom elevation Layer 3

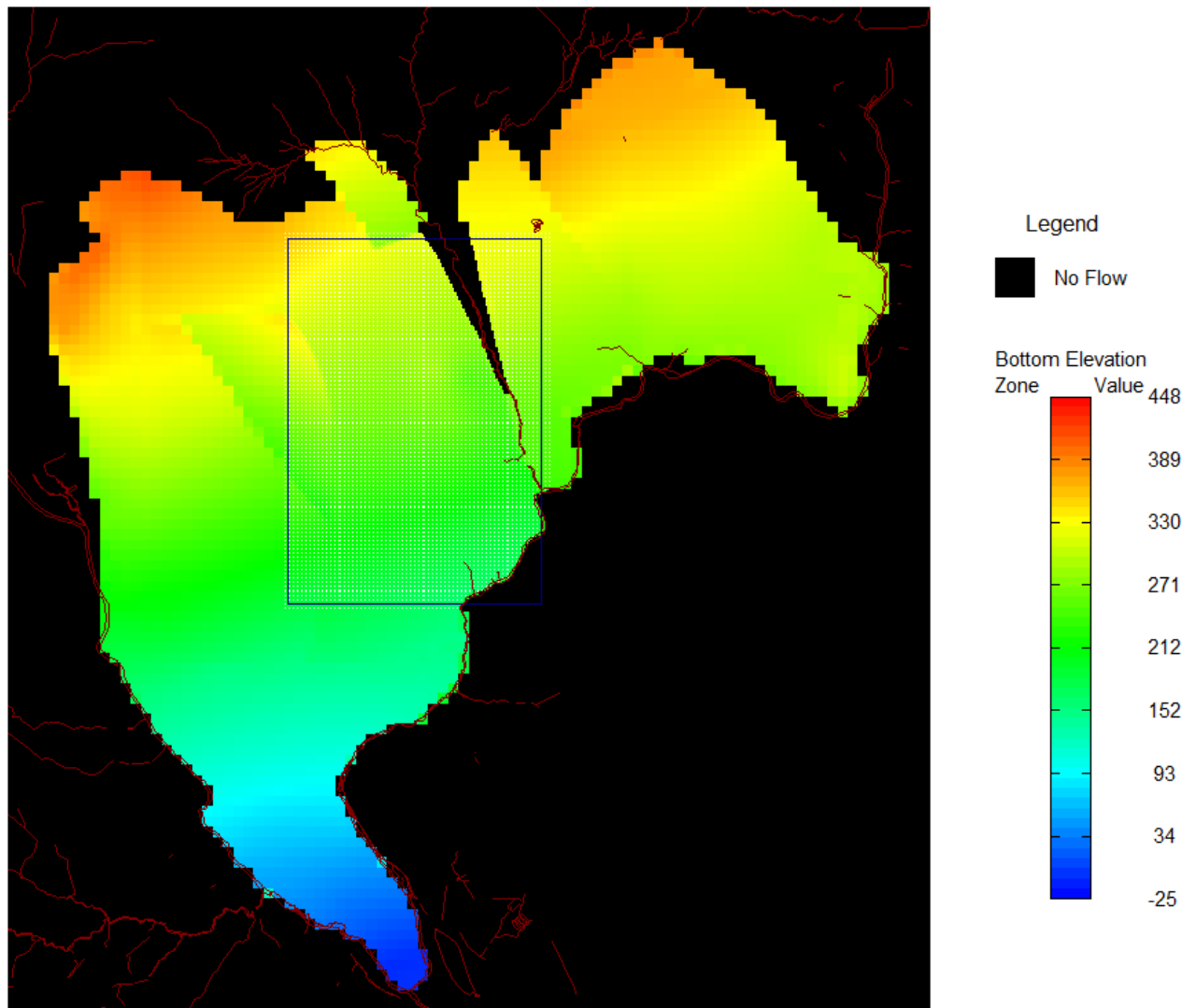
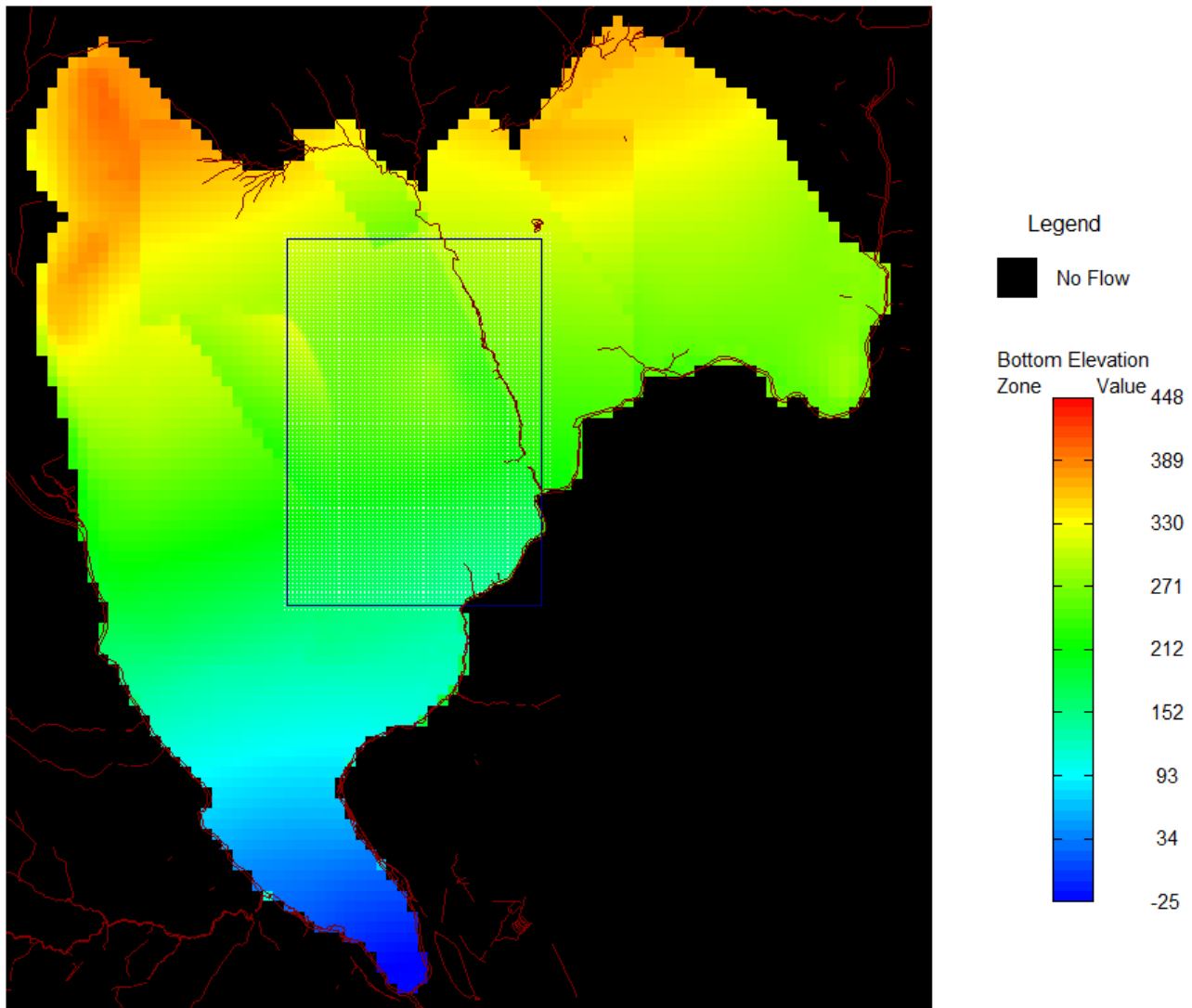


Figure 2.9 Bottom elevation Layer 4

2.2.4 External boundaries

External model boundaries to the north, north-west and east have been set as no-flow boundaries. These boundaries coincide with the outcrop of the Cwmyniscoy Mudstone Formation upper boundary to the north and north-west and older faulted strata to the east. Elsewhere, rivers form the model boundaries. These rivers are the Taf Fawr in the west and the Taf Fechan in the south. The model extends southwards to the confluence between the Taf Fawr and Taf Fechan. The model boundaries are shown on Figure 2.1 to Figure 2.4 where the river boundary conditions are shown in green.

The Taf Fawr and Taf Fechan have been represented in the model as river boundary conditions. River boundary properties are given in Table 2.2. Each river in each model layer is assigned a unique reach number to facilitate boundary condition modification. River bottom elevations have been estimated from the Digital Terrain Data available for the study area and the stage has been set at 0.45 m above the river bottom, based on field observation estimates. River widths have been estimated based on field observation. The river length is set to the model cell dimension, either 50 m in the parent cells or 10 m in the nested cells. In the absence of any data, the bed thickness is

arbitrarily set at 1 m. On the basis of model calibration (Section 2.3), the hydraulic conductivity of the riverbed material is set to be a factor 50 lower than the aquifer hydraulic conductivity of that layer.

As the Nant y Glais is considered to be gaining throughout the study area, it is represented in the model as drain cells. Drain cell properties for this watercourse are also shown on Table 2.2. The drain elevation is set to the top of the relevant model cells. Figure 2.1 to Figure 2.4 show drain cells in yellow. The majority of this watercourse is located within model Layer 4 (Abercriban Oolite Subgroup), with limited reaches within Layer 3 (Llanelly Formation) and Layer 2 (Dowlais Limestone Formation).

Table 2.2 River boundary properties

Watercourse	Reach	Type	Layer	From	To	Width	River Bottom Start	River Bottom End	Length	Bed thickness	Grid
Taf Fawr	1	River	1	302725, 208075	303725, 207225	20	195.65	175.85	50	1	Parent
Taf Fawr	2	River	2	302225, 208975	302725, 208125	15	208.15	195.95	50	1	Parent
Taf Fawr	3	River	3	302225, 209125	302225, 209025	12	209.55	208.45	50	1	Parent
Taf Fawr	4	River	4	302125, 209525	302225, 209175	12	213.35	210.35	50	1	Parent
Taf Fechan	5	River	1	303425, 208025	303775, 207275	15	189.95	176.75	50	1	Parent
Taf Fechan	6	River	1/2	303375, 208125	303425, 208075	10	191.95	191.35	50	1	Parent
Taf Fechan	7	River	2	304355, 209635	303955, 209055	12	230.05	217.35	10	1	Nested
Taf Fechan	8	River	3	304385, 209645	304365, 209635	14	230.35	230.25	10	1	Nested
Taf Fechan	9	River	4	304395, 209655	304385, 209655	14	230.35	230.35	10	1	Nested
Taf Fechan	10	River	4	305575, 210125	304425, 209675	12	269.90	230.35	50	1	Parent
Taf Fechan	11	River	3/4	305975, 210775	305675, 210075	12	287.75	272.05	50	1	Parent
Nant y Glais	5	Drain	2	303725, 211025	303775, 210975	3	324.21	318.62	50	1	Parent
Nant y Glais	5	Drain	2	304065, 210355	304355, 209645	3	233.41	233.41	10	1	Nested
Nant y Glais	6	Drain	3	304185, 210165	304345, 209665	3	271.45	233.88	10	1	Nested
Nant y Glais	7	Drain	4	303775, 210925	303875, 210925	3	284.96	315.75	50	1	Parent
Nant y Glais	7	Drain	4	303855, 210895	304305, 209755	3	315.43	242.46	10	1	Nested

2.2.5 Internal boundaries

Springs identified in Section 2.5.3 of Stantec (2020) have been included within the model as drain cells and are summarised in Table 2.3. With the exception of the Quarry Processing Area Spring (discussed below), the base and top elevation of each cell was used to determine which layer to insert the drain cell. The drain elevation was determined by setting it to 0.2 m below the top of the model cell on the basis that the springs are from the Limestone and there will be a nominal thickness of soil cover above the Limestone. All the spring drains are located in Layer 2 (Dowlais Limestone Formation) except for NG03 which is located in the Layer 4 (Abercriban Oolite) due to the fact that the river is deeply incised at this location. In order to assist with model calibration and reporting, the springs along the Nant y Glais are defined as being in Reach 1 whilst those along the Cwm Taf Fechan are assigned to Reach 2. A spring has also been identified in the Quarry Processing Area as shown on Figure 2.9 of Stantec (2020). This spring is also represented in the model with its head set at the same elevation as the top of the Layer 2 (i.e at the ground surface). This Spring was inserted directly into Layer 2.

Table 2.3 Spring boundary conditions included within the model

Spring	Easting (m)	Northing (m)	Base (mAOD)	Top (mAOD)	Elevation (mAOD)	Layer	Reach
CTFW01	304023	209209	185.465	229.242	229.042	2	2
CTFW02	304115	209218	184.722	227.492	227.292	2	2
CTFW03	304119	209249	187.607	229.551	229.351	2	2
CTFW04	304137	209249	187.224	228.436	228.236	2	2
CTFW05/06	304177	209284	190.312	233.315	233.115	2	2
CTFW07	304228	209308	191.208	229.448	229.248	2	2
CTFW08	304307	209451	203.631	231.286	231.086	2	2
NG01	304118	210226	275.025	279.11	278.91	2	1
NG02	304132	210195	271.865	274.858	274.658	2	1
NG03	303991	210610	282.999	304.519	304.319	4	1
Blaenglais	303507	210920	288.793	340.008	339.808	2	1
Quarry processing area	303655	209593	231.111	268.709	268.709	2	8

Groundwater also discharges to the quarry base. The quarry area has been defined as a series of drain cells within model Layer 2 (Dowlais Limestone Formation). The drain cell head has been defined as the ground surface, which is the top elevation of Layer 2, as the geological formations represented in Layer 1 are not present at the Site. The drain cells on the western quarry limb are assigned to Reach 3 and those on the western limb to Reach 4.

Groundwater which drains into the quarry base is re-introduced into the aquifer at the infiltration ponds which are shown on Figure 2.2. The infiltration ponds are represented by fixed heads in the model. The head was initially fixed at the lowest ground level within the area of the ponds and this was then adjusted via calibration as detailed in Section 2.3.

2.2.6 Groundwater abstractions

Stantec (2020) states that there are no major groundwater abstractions in the model area. Private water supplies are small abstractions and these (where present) have not been included in the model as they are not considered to significantly impact groundwater flows or levels at the scale of interest.

2.2.7 Hydraulic parameters

The distribution of hydraulic conductivity within limestone units of this nature is typically complex, and the flowing zones are likely to be dominated by fractures and fissures. Representation of such heterogeneous systems in porous flow medium models such as MODFLOW is difficult and therefore the hydraulic conductivity has been selected on the basis of model calibration, which is discussed in Section 2.3. On this basis of model calibration, the hydraulic conductivity for the layers has been defined as follows.

- Layer 1: Strata overlying the Dowlais Limestone Formation 0.15 – 0.25 m/d
- Layer 2: Dowlais Limestone Formation 0.15 – 0.25 m/d
- Layer 3: Llanelly Formation – horizontal 0.001, vertical 0.0001 m/d
- Layer 4 Abercriban Oolite Subgroup 0.15 – 0.25 m/d

It should be noted that these hydraulic conductivity values represent the weighted average of the limestone fissures and matrix. In reality, the majority of the flow is likely to be concentrated within a small volume of high hydraulic conductivity fissures.

2.2.8 Recharge

Recharge is set to the highest active layer with a value of 227 mm/a (0.000622 m/d) based on the Q_{95} estimated recharge for the Taf at Merthyr Tydfil catchment (Table 2.4 of Stantec, 2020) in which the Site is located.

2.3 Calibration to Existing Conditions

As noted in Section 2.2.7, the model has been calibrated by adjusting the hydraulic conductivity of the model layers so as to obtain a best fit of calculated head against long term average observed head at the monitoring wells. Long term average observed groundwater levels have been used as the model is a steady state model that represents long term average conditions.

Due to uncertainty in the model calibration, results for two model runs are presented with

- Layer 2 (Dowlais Limestone) and Layer 4 (Abercriban Oolite Subgroup) set to 0.15 m/d and
- Layer 2 (Dowlais Limestone) and Layer 4 (Abercriban Oolite Subgroup) set to 0.25 m/d.

We note that the model with the hydraulic conductivity set to 0.25 m/d does not converge. However, inspection of the model suggests that this is due to localised convergence issues around areas of dry cells and the overall water balance for the model is acceptable (see Table 2.4).

It was also found during model calibration that using a hydraulic conductivity the same as the aquifer hydraulic conductivity for the Taf Fawr and Taf Fechan river boundary conditions (i.e. no restriction on the discharge of groundwater into the river cells or recharge from the river cells to groundwater) resulted in no flow at the Taf Fechan springs as the predicted water level was below ground level at these springs. By reducing the hydraulic conductivity of the riverbed material, a restriction is placed on groundwater discharge to the river cells and the heads adjacent to the river cells are raised above

ground level, thus inducing spring flows. The best fit to observed data was achieved by setting the river bed hydraulic conductivity a factor 50 lower than the aquifer hydraulic conductivity.

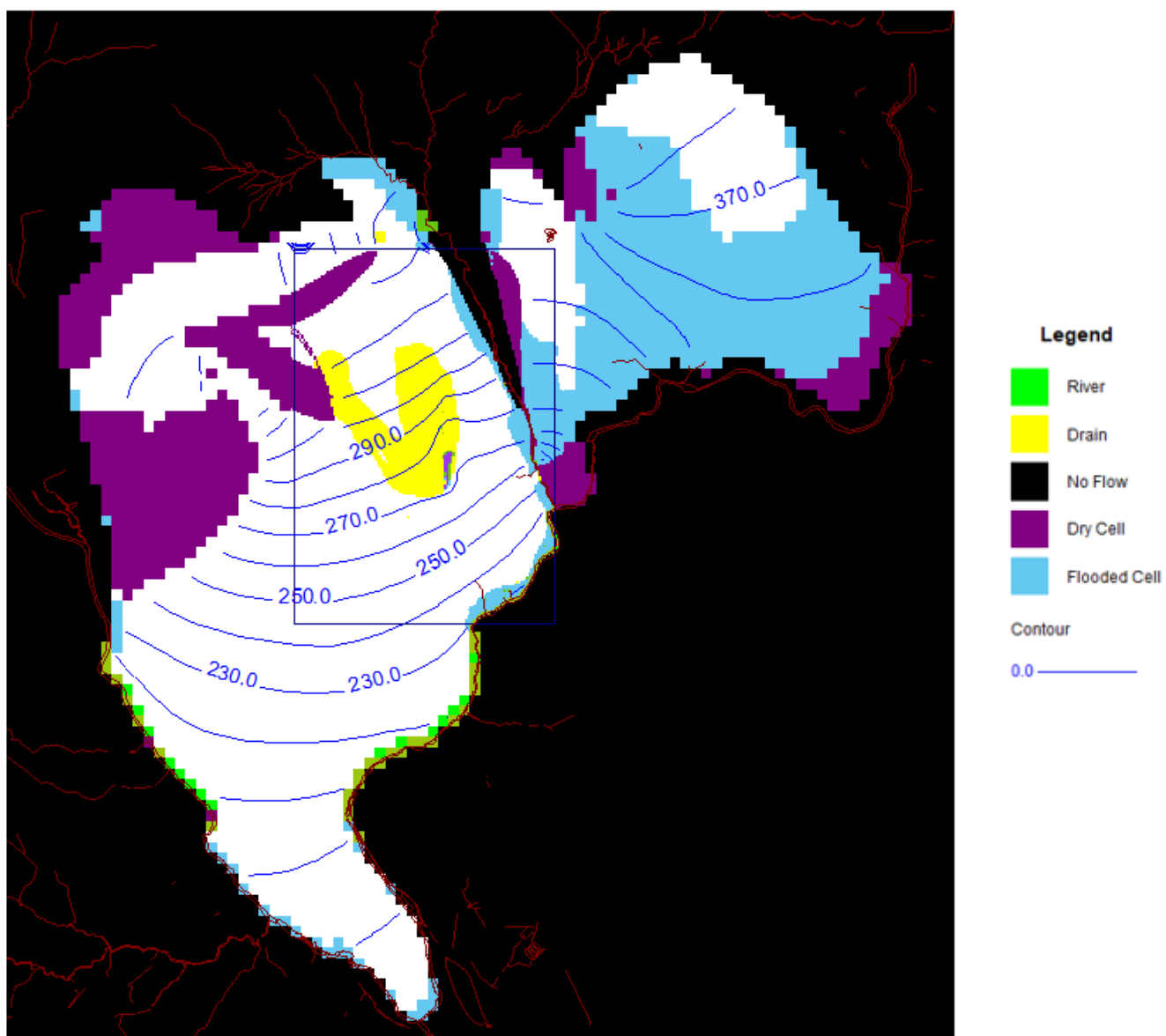
Finally, in order to obtain a realistic infiltration from the infiltration ponds, the infiltration pond fixed head was adjusted as detailed in Section 2.3.2.

2.3.1 Predicted heads

Predicted heads in the two main aquifers - Layer 2 (Dowlais Limestone) and Layer 4 (Abercriban Oolite Subgroup) - are shown on Figure 2.10 and Figure 2.11 for the model run where the hydraulic conductivity of these strata was set to 0.25 m/d.

In Layer 2, heads on the western side of Nant y Glais show a groundwater flow direction to the south, towards the river boundaries. In the north-west and west of the model, the layer is dry (purple cells) indicating that the limestone in these areas is simulated as being fully unsaturated. On the eastern side of Nant y Glais, the heads are often above the top of Layer 1 implying that the ground surface is flooded. Clearly this is not the case in reality, and it is likely that additional drain cells are required to drain water from the Limestone in this area, discharging into Nant y Glais, Taf Fechan and at other spring locations. Given the location of the Quarry in the western area, it is not considered that this issue is significant in terms of the Quarry water balance.

In Layer 4, the groundwater flow direction is also to the south (Figure 2.11), towards the river boundary conditions. An inflection in the contours can be seen where groundwater discharges to Nant y Glais which lies in a steeply incised valley and is in hydraulic continuity with the Abercriban Oolite Subgroup.

Figure 2.10 Predicted heads in Layer 2: hydraulic conductivity 0.25 m/d

Note that within the excavation area, small blocks of green cells are flooded cells and purple cells are flooded cells overlying the blue constant head cells representing the eastern infiltration pond

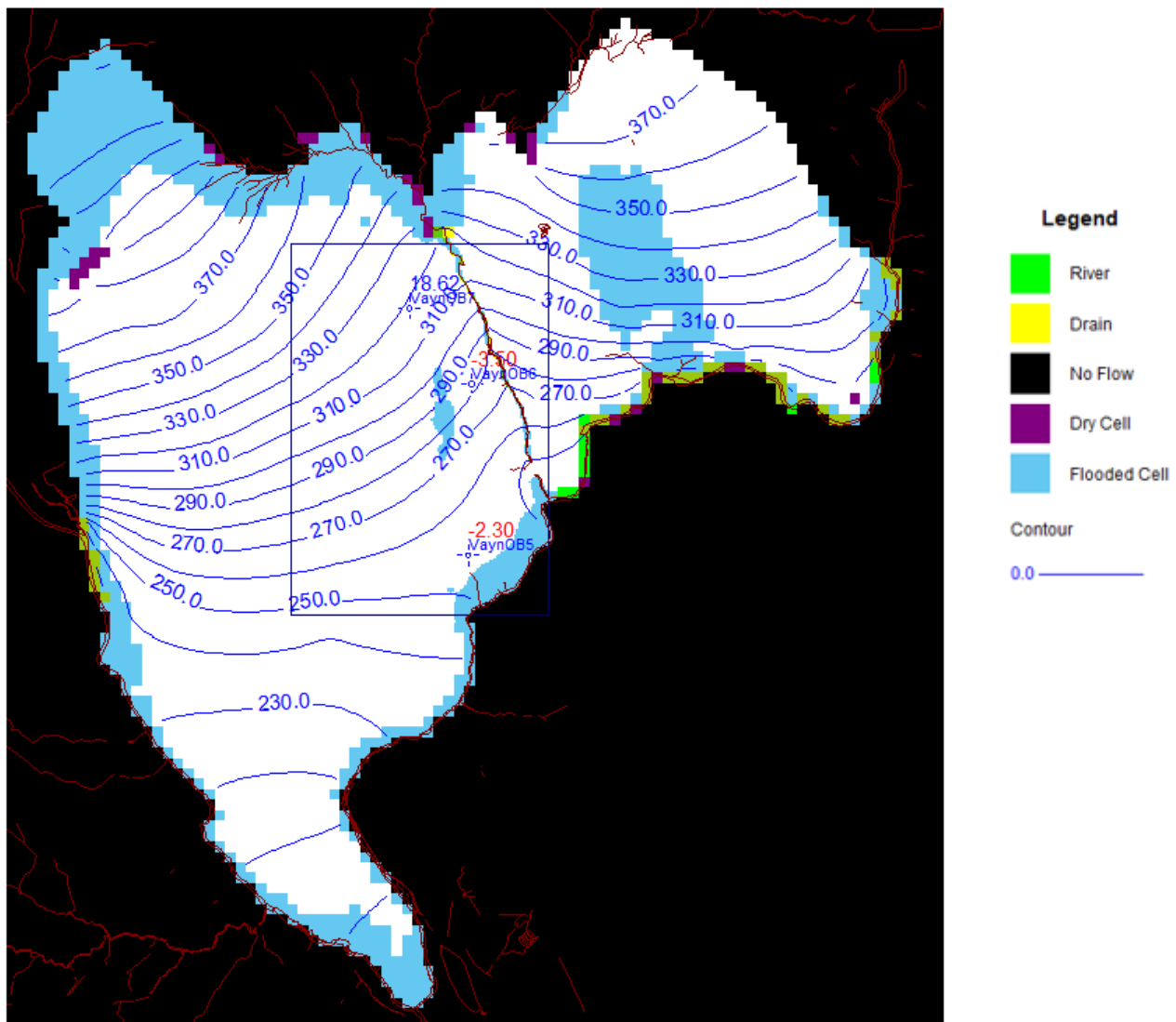
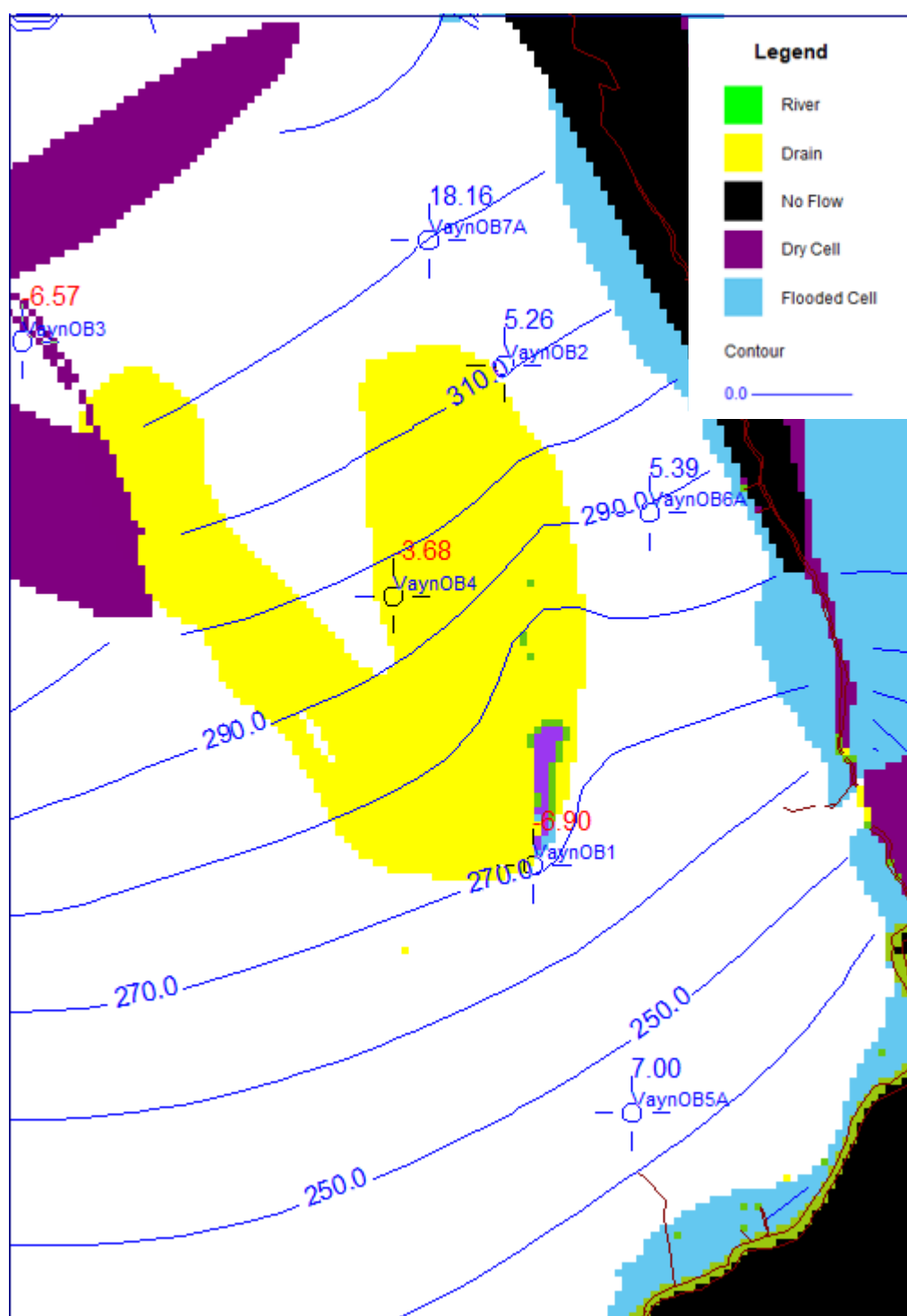
Figure 2.11 Predicted heads in Layer 4: hydraulic conductivity 0.25 m/d

Figure 2.12 shows modelled heads in the vicinity of the Site for the model with the hydraulic conductivity set to 0.25 m/d. The current excavation area can be clearly seen on this figure as it is represented by the yellow drain boundary condition cells. Note that the drain cells were removed from the area of the western infiltration pond, but not replaced by constant head cells as detailed below. These cells are shown in white on the figure. The eastern infiltration pond is shown in purple (constant head boundaries are blue and this is overlain by pale blue flooded cells giving a resulting colour of purple). The site monitoring wells are also shown. The residual (difference between modelled head and observed head) is posted on this figure. Where the residual is shown in blue, the modelled head is lower than observed and where it is shown in red, it is higher.

Modelled heads to the east of the Site are lower than observed by between 5.26 m at VaynOB2 and 18.16 m at VaynOB7A. To the north-west (at VaynOB3) heads are higher than observed by 6.57 m), but it is noted that this area is very close to dry cells and the modelled heads here may not be accurate. To the south-east (at VaynOB05A) modelled heads are lower than observed by 7 m. At the Site itself the head at VaynOB1 is 6.90 m higher than the observed head and at VaynOB4, it is 3.68 m higher.

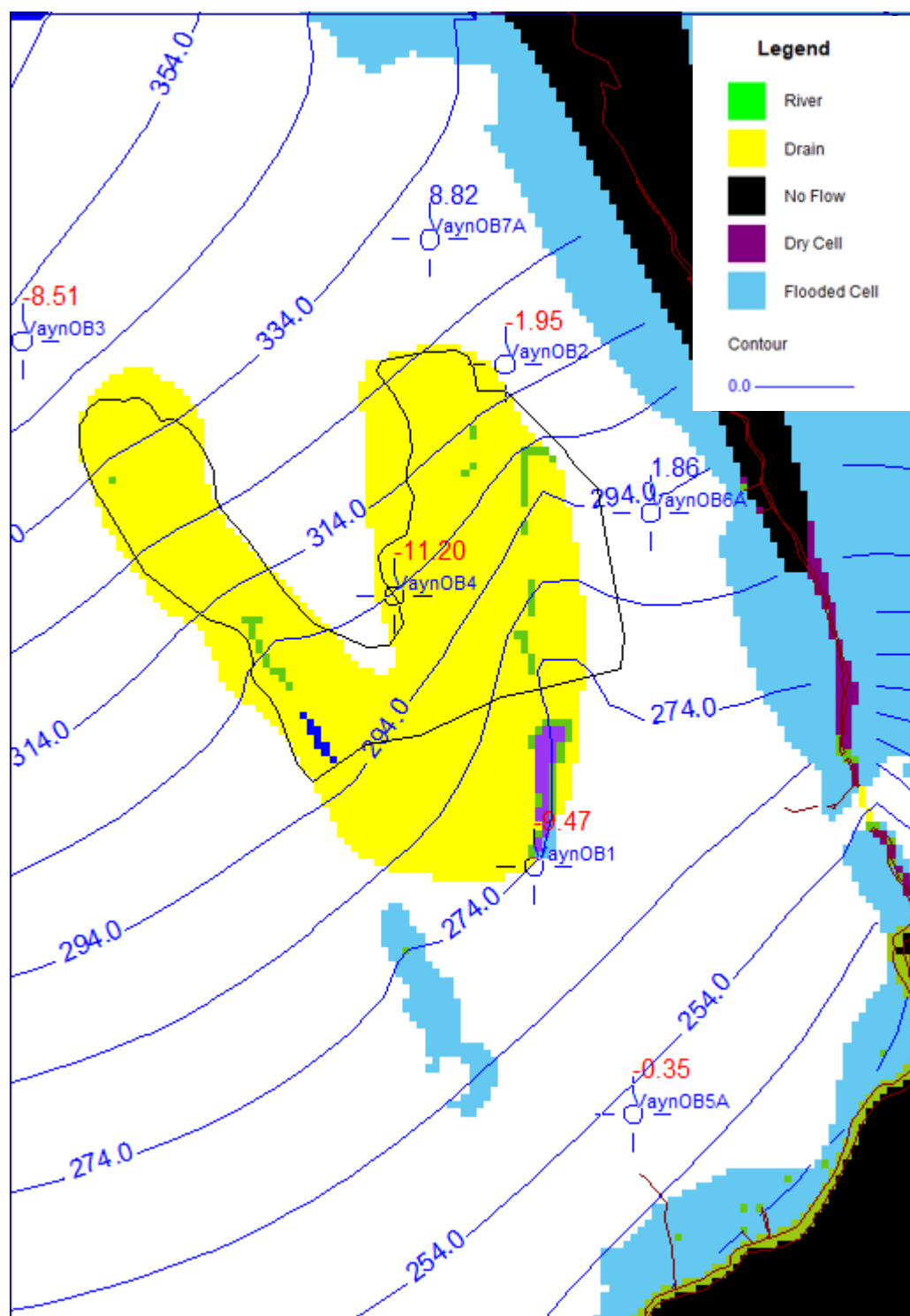
Figure 2.12 Predicted heads in vicinity of Site in Layer 2: hydraulic conductivity 0.25 m/d

Note that within the excavation area, small blocks of green cells are flooded cells and purple cells are flooded cells overlying the blue constant head cells representing the eastern infiltration pond

A general improvement in model calibration can be achieved by decreasing the hydraulic conductivity of Layer 2 (Dowlais Limestone) and Layer 4 (Abercriban Oolite Subgroup) to 0.15 m/d (Figure 2.13). In this model, modelled heads at two of the observation wells to the east remain too low, but VaynOB2 is now slightly too high. Heads are increased to the north-west resulting in an even poorer calibration in this area. They are also very slightly too high to the south-east at

VanOB5A. However, within the Site itself, at VaynOB1 and VaynOB4 the calibration is significantly poorer, with the modelled head significantly higher than observed.

Figure 2.13 Predicted heads in vicinity of Site in Layer 2: hydraulic conductivity 0.15 m/d



Note that within the excavation area, small blocks of green cells are flooded cells and purple cells are flooded cells overlying the blue constant head cells representing the infiltration ponds

Obtaining an improved calibration would necessitate introducing additional hydraulic conductivity and / or recharge zones into the model and there is limited field evidence to support this. Given the

difficulties in using heads measured within fissured strata to calibrate a porous medium flow model, it is not considered worthwhile to attempt this.

With the higher hydraulic conductivity of 0.25 m/d (and the better calibration within the vicinity of the Site), Figure 2.12 shows a small inflection in the contours within the eastern quarry area as groundwater is drained via the drain cells. At a few localised areas on the eastern limb, the model shows the groundwater head above ground level (blue / green areas and purple areas over the infiltration pond) implying that groundwater fed ponds would develop here. However, across most of the eastern limb and all of the western limb, the drain cells are generally above the water table, so only limited drainage occurs. This is clearly inconsistent with site observations which suggest there are spring flows on both the eastern and western limbs. However, it is possible that these springs are fed by perched water that is disconnected from the regional system and would not be represented by this model.

Similarly, the groundwater level at the Quarry Processing Area spring is simulated at 267 mAOD which is below the spring elevation of 268.71 mAOD, so no discharge is simulated here. Again, this may imply that this spring is fed by perched groundwater.

With the lower hydraulic conductivity of 0.15 m/d (Figure 2.13), heads in the vicinity of the Site are significantly higher and we now see a more significant inflection in the groundwater contours and more areas where the water table is shown to be above ground level (blue / green areas and purple areas over the infiltration ponds) within both the eastern and western quarry limbs.

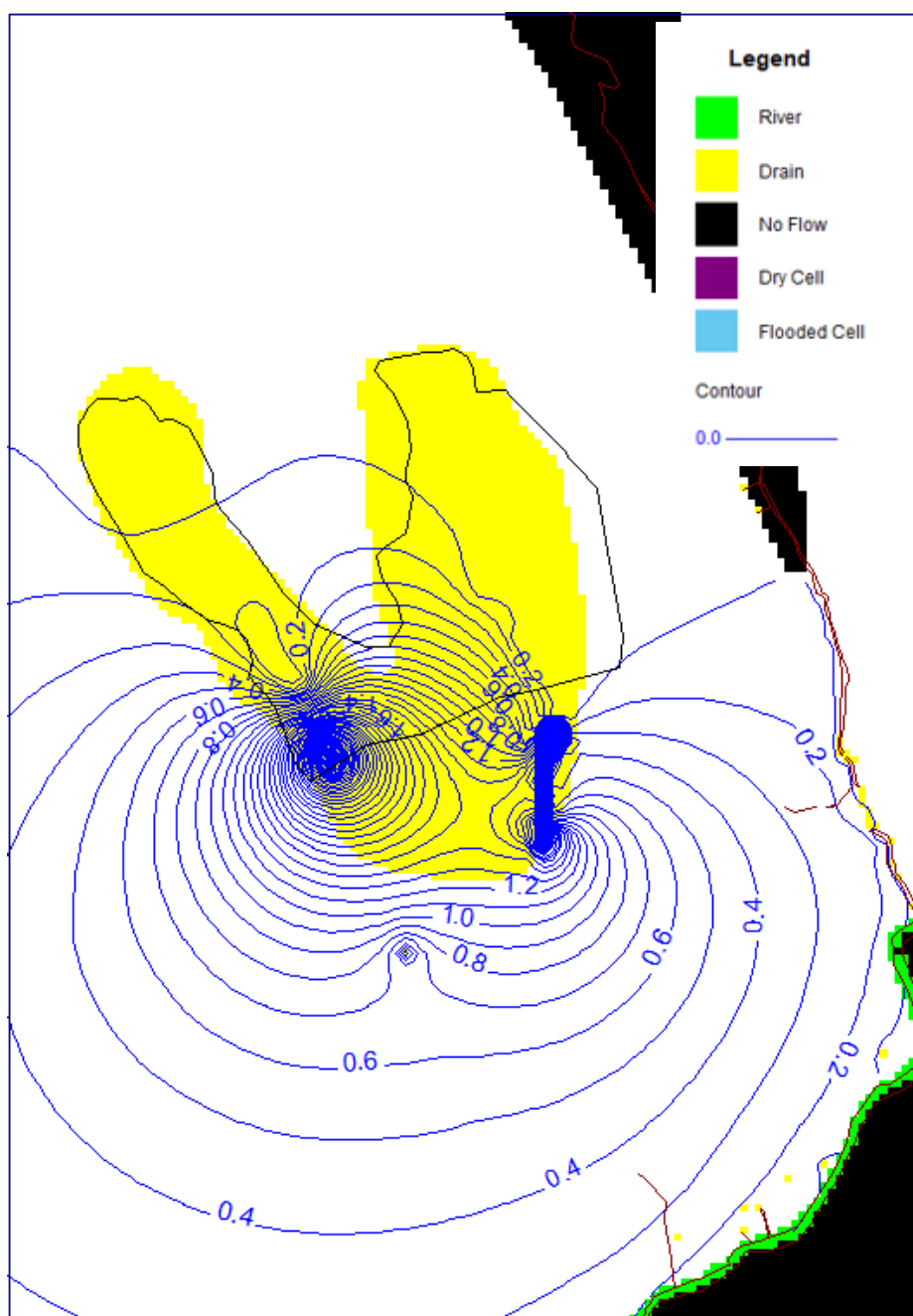
The groundwater level at the Quarry Processing Area spring is now 271 mAOD which is above ground level. In fact, an area of flooded ground (blue area on Figure 2.13) is now simulated.

Figure 2.11 also shows the modelled residuals for the two observation wells in Layer 4 (Abercriban Oolite Subgroup). The heads are slightly too high in the south at VaynOB5 and higher still to the north at VaynOB6. As the heads are constrained to the south by the rivers, this implies the hydraulic conductivity of this layer is too low, causing the hydraulic gradient to be too steep.

The hydraulic conductivity of Layer 3 has been set to a horizontal hydraulic conductivity of 0.001 m/d and vertical of 0.0001 m/d. The vertical hydraulic conductivity has been set lower than the recharge rate to prevent significant downwards flows from Layer 2 (Dowlais Limestone) to Layer 4 (Abercriban Oolite Subgroup). It was found without this hydraulic barrier, groundwater in Layer 2 in the vicinity of the Site flowed downwards into Layer 4 to discharge into Nant y Glais and it was not possible to maintain heads in Layer 2 high enough. This suggests that there may be limited spring discharge along the Nant y Glais valley sides from the Dowlais Limestone.

Figure 2.14 shows the difference in heads between the low hydraulic conductivity model and a low hydraulic conductivity model variant that does not simulate the infiltration ponds. The greatest head difference is at the infiltration ponds themselves where water is being recharged to the groundwater system. The head difference dissipates with distance from the infiltration ponds. The figure shows that there is a positive head difference some distance to the north of the ponds and also between them. This increase in heads within the vicinity of the model drains illustrates a certain amount of re-circulation of water within the model between the quarry springs (represented in the model as drains) and the infiltration ponds (represented in the model as fixed heads). Whether or not this is a real effect will depend on the actual geometry of the fissures within the Limestone stratum. Assuming that the bulk of groundwater flow is within the fissures, the majority of the flux from the infiltration ponds will be to wherever fissures connecting these ponds discharge.

Figure 2.14 Difference between V5.23C (Western pond fixed head at 299.546 & eastern pond at 270.244) – V5.21A (No additional recharge from infiltration ponds & no drain cells at ponds).



2.3.2 Water balance

The water balance for the model with the higher limestone hydraulic conductivity (0.25 m/d) is presented in Table 2.4 and for the lower hydraulic conductivity (0.15 m/d) in Table 2.5. The model with the higher hydraulic conductivity has a smaller discharge to the drain cells (as the water table is lower) and a proportionately higher discharge to the river cells.

Table 2.4 Model water balance: hydraulic conductivity 0.25 m/d

Description	Inflow (m ³ /d)	Outflow (m ³ /d)
Recharge	5.95E+03	0.00E+00
Constant head	4.59E+02	2.70E+01
River	0.00E+00	4.61E+03
Drain	0.00E+00	1.80E+03
TOTAL	6.41E+03	6.41E+03
ERROR	-7.63E-06	

Table 2.5 Model water balance: hydraulic conductivity 0.15 m/d

Description	Inflow (m ³ /d)	Outflow (m ³ /d)
Recharge	5.95E+03	0.00E+00
Constant head	2.96E+02	1.86E+01
River	0.00E+00	4.26E+03
Drain	0.00E+00	1.97E+03
TOTAL	6.25E+03	6.25E+03
ERROR	-3.04E-05	

The river fluxes by reach for the higher hydraulic conductivity model are presented in Table 2.6 and for the lower hydraulic conductivity run in Table 2.7. The proportion of water discharging to each river remains the same (discharge to Taf Fawr is 0.6 times the discharge to Taf Fechan), which is expected as the flow directions in the two models are largely the same, it is just the heads and gradients which have changed.

Table 2.6 River boundary fluxes by reach: hydraulic conductivity 0.25 m/d

Watercourse	Layer	Reach or Zone	Calibrated model river flux (m ³ /d)
Taf Fawr	1	1	-692
Taf Fawr	2	2	-563
Taf Fawr	3	3	-49
Taf Fawr	4	4	-459
Taf Fawr Total			-1,763
Taf Fechan	1	5	-221
Taf Fechan	1/2	6	-878
Taf Fechan	2	7	-494
Taf Fechan	3	8	-1
Taf Fechan	4	9	-17
Taf Fechan	4	10	-934

Taf Fechan	3/4	11	-301
Taf Fechan Total			-2,846

Note: negative values represent flows out of the model domain i.e. groundwater discharge to rivers

Table 2.7 River boundary fluxes by reach: hydraulic conductivity 0.15 m/d

Watercourse	Layer	Reach or Zone	Calibrated model river flux (m ³ /d)
Taf Fawr	1	1	-602
Taf Fawr	2	2	-649
Taf Fawr	3	3	-50
Taf Fawr	4	4	-329
Taf Fawr Total			-1,630
Taf Fechan	1	5	-208
Taf Fechan	1/2	6	-824
Taf Fechan	2	7	-415
Taf Fechan	3	8	-1
Taf Fechan	4	9	-21
Taf Fechan	4	10	-829
Taf Fechan	3/4	11	-330
Taf Fechan Total			-2,628

Note: negative values represent flows out of the model domain i.e. groundwater discharge to rivers

The spring flows by reach for the higher hydraulic conductivity model are presented in Table 2.8 and for the lower hydraulic conductivity run in Table 2.9. This shows that there are higher spring discharges with the lower hydraulic conductivity model which has higher groundwater heads.

In the model with the higher hydraulic conductivity, the western limb of the Site and the Quarry Processing Area spring are not simulated as having any groundwater discharge; these flows must be from perched water in this scenario. To balance, the constant head cells for the western infiltration pond were removed from the model to ensure no water is recharged to the aquifer on this side. The eastern limb has a groundwater discharge of 576 m³/d from the springs. Initially, with the eastern infiltration pond constant head set to ground level, there was actually an inflow from groundwater to this infiltration pond which clearly does not match observation. As noted in Section 2.3.1 the modelled heads are 6.90 m too high in the vicinity of VaynOB1, which is located just to the south of the infiltration pond. Therefore, the constant head was increased such that it recharged groundwater. By raising the constant head from 270.244 mAOD to 275.00 mAOD, a recharge flux of 456 m³/d was generated. This is still smaller than the spring flow and allows for some of the spring flow to be lost to surface water and / or evaporation. This difference could also be due to the re-circulation of water from the infiltration ponds to the quarry springs (drain cells) which may or may not actually occur, depending on the orientation and transmissivity of fissures in the vicinity of the infiltration ponds.

Table 2.8 Spring and infiltration pond flows: hydraulic conductivity 0.25 m/d

Spring group	Layer	Reach	Drain flux (m ³ /d)
Nant y Glais springs (including Blaenglais Spring)	1 & 4	1	-15.18
Cwm Taf Fechan springs	2	2	-36.17
Quarry base - western limb	2	3	0.00
Quarry base - eastern limb	2	4	-576.19
Quarry base – total	2	3 & 4	-576.19
Infiltration pond - western limb	2	1	0.00
Infiltration pond - eastern limb	2	2	456.23
Infiltration pond - total	2	1 & 2	456.23
Nant y Glais river	2	5	-210.38
Nant y Glais river	3	6	-5.09
Nant y Glais river	4	7	-954.08
Nant y Glais river total			-1,170
Quarry Processing Area	2	8	0.00

Note: negative values represent flows out of the model domain i.e. groundwater discharge to springs

In the lower hydraulic conductivity model, the springs on the western limb generate 131 m³/d of discharge. With the western infiltration pond constant head set at ground level (299.546 mAOD), a recharge flux of 54 m³/d is generated. The springs on the eastern limb generate 541 m³/d of water. As with the higher hydraulic conductivity model, the constant head had to be raised to generate recharge. With a constant head of 275 mAOD, 277 m³/d of recharge is generated.

Table 2.9 Spring and infiltration pond flows: hydraulic conductivity 0.15 m/d

Spring group	Layer	Reach	Drain flux (m ³ /d)
Nant y Glais springs (including Blaenglais Spring)	1 & 4	1	-15.33
Cwm Taf Fechan springs	2	2	-52.85
Quarry base - western limb	2	3	-130.79
Quarry base - eastern limb	2	4	-541.20
Quarry base – total	2	3 & 4	-671.99
Infiltration pond - western limb	2	1	53.99
Infiltration pond - eastern limb	2	2	223.10
Infiltration pond - total	2	1 & 2	277.10
Nant y Glais river	2	5	-207.96
Nant y Glais river	3	6	-6.02

Spring group	Layer	Reach	Drain flux (m ³ /d)
Nant y Glais river	4	7	-962.95
Nant y Glais river total			-1,177
Quarry Processing Area	2	8	-55.74

Note: negative values represent flows out of the model domain i.e. groundwater discharge to springs

Section 9.3.3 of the HIA (Stantec, 2020) suggests that the total groundwater discharge to the quarry is of the order of 10 l/s. The higher hydraulic conductivity model simulates a discharge of 6.7 l/s and the lower hydraulic conductivity model a discharge of 7.8 l/s. The balance of the discharge may be from perched water which is not simulated by the model.

2.3.3 Comparison of river and spring flows with observed data

2.3.3.1 Nant y Glais

Measured flows at Aberglais (Figure 9.11 of Stantec, 2020) vary between 14.21 & 150.75 l/s, but the hydrograph suggests that stream flow is dominated by runoff and interflow and that baseflow derived from groundwater discharge is likely to comprise a small component of the total flow. Table 2.5 of the HIA gives the modelled 95% exceedance as 9.4 l/s which is just a little lower than the modelled discharge to this river which is between 13.54 l/s for the high hydraulic conductivity model and 13.62 l/s for the low hydraulic conductivity model.

2.3.3.2 Nant y Glais springs

Section 2.5.3 of the HIA states that the northernmost spring (NG03) was observed to flow at <1 l/s. The model grid resolution cannot differentiate between this spring and the Nant y Glais river, the combined drain discharge at this location is 0 l/s in the higher K model & 0.05 l/s in the lower K model.

Section 2.5.3 of the HIA states that the southernmost spring (NG02) was observed to flow at around 10 l/s. It is not known the proportions of runoff, inflow, perched and regional groundwater that make up this flow. The high hydraulic conductivity model has a discharge of 0.17 l/s & the low hydraulic conductivity model a discharge of 0.15 l/s to this spring.

Section 2.5.3 of the HIA states that the spring marked as NG01 is mostly dry. Both model variants show no discharge at this location.

2.3.3.3 Taf Fechan springs

There are no quantitative flow data for these springs against which to compare the modelled discharges, although qualitative observations of spring flows have been made.

The model predicted discharge for all springs combined is between 0.42 l/s for the high hydraulic conductivity and 0.61 l/s for the low hydraulic conductivity model. However, we note that as these are fissure discharges and the vast majority of the flow will occur in the fissures as opposed to the matrix, it is probably more appropriate to compare the observed spring flows with the total discharge along the line of the springs in the porous medium flow model. Since all the flow must discharge to the Taf Fechan River, an upper limit of the spring flow can be estimated by including the groundwater discharge flux to the River as well as the spring discharges. The River is in Reach 7 in the model and this discharge is 5.72 l/s for the high hydraulic conductivity model and 4.80 l/s for the low hydraulic conductivity model. Therefore, a reasonable estimate for fissure flow discharge to the springs might be 5 l/s.

Site observations suggest that 5 l/s is probably a reasonable flow for the combined Taf Fechan springs. We note that the flow from these springs varied quite considerably from month to month, both in terms of the total volume of water and the number of springs from which a flow was observed. This suggests a component of surface runoff or interflow may be contributing to the total observed spring flow which is not simulated by the model.

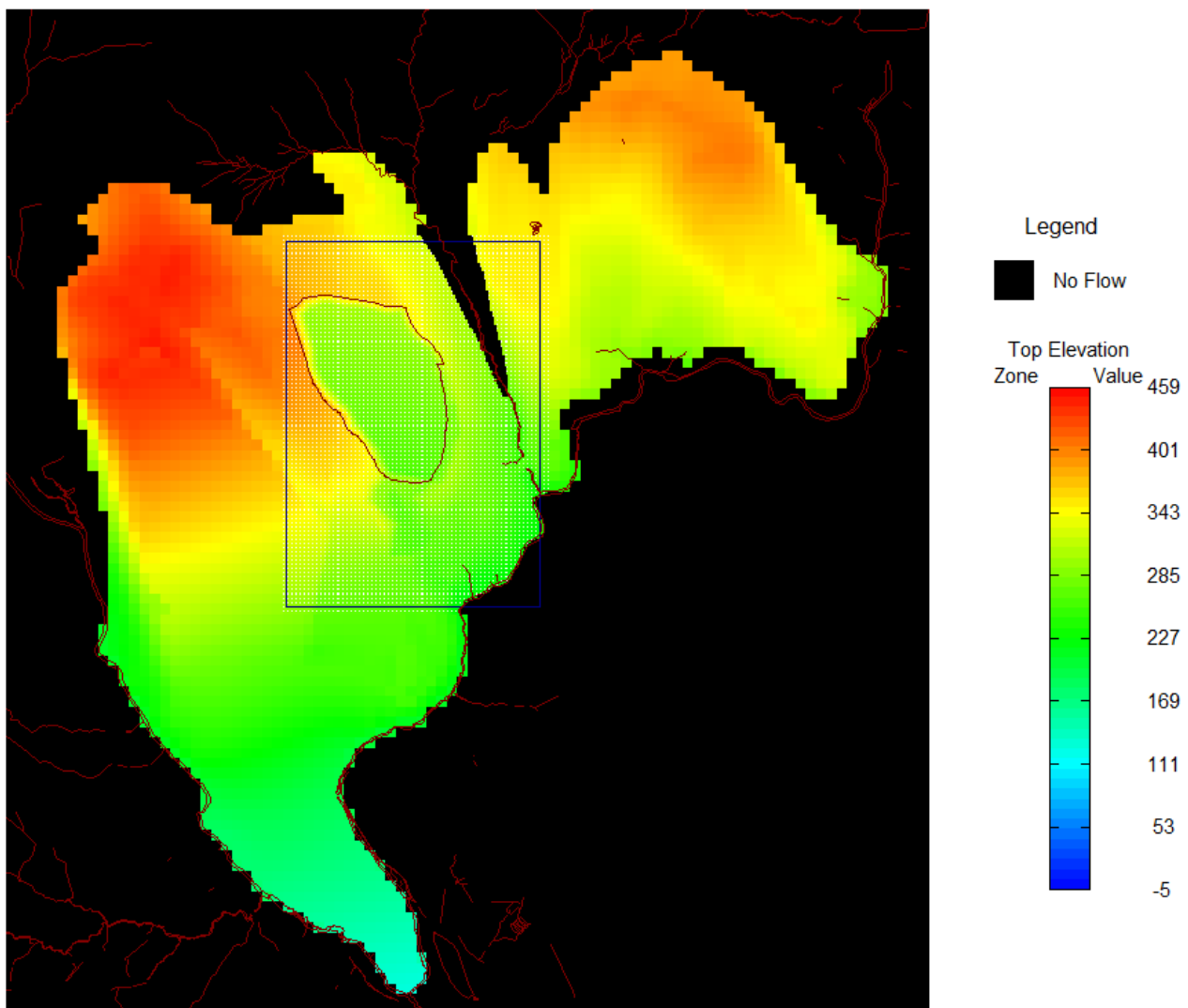
3 Post-Quarrying Predictive Run

3.1 Model Construction

The calibrated models were used as the starting points for the predictive run models. A prediction model was developed for the higher and lower hydraulic conductivity variants.

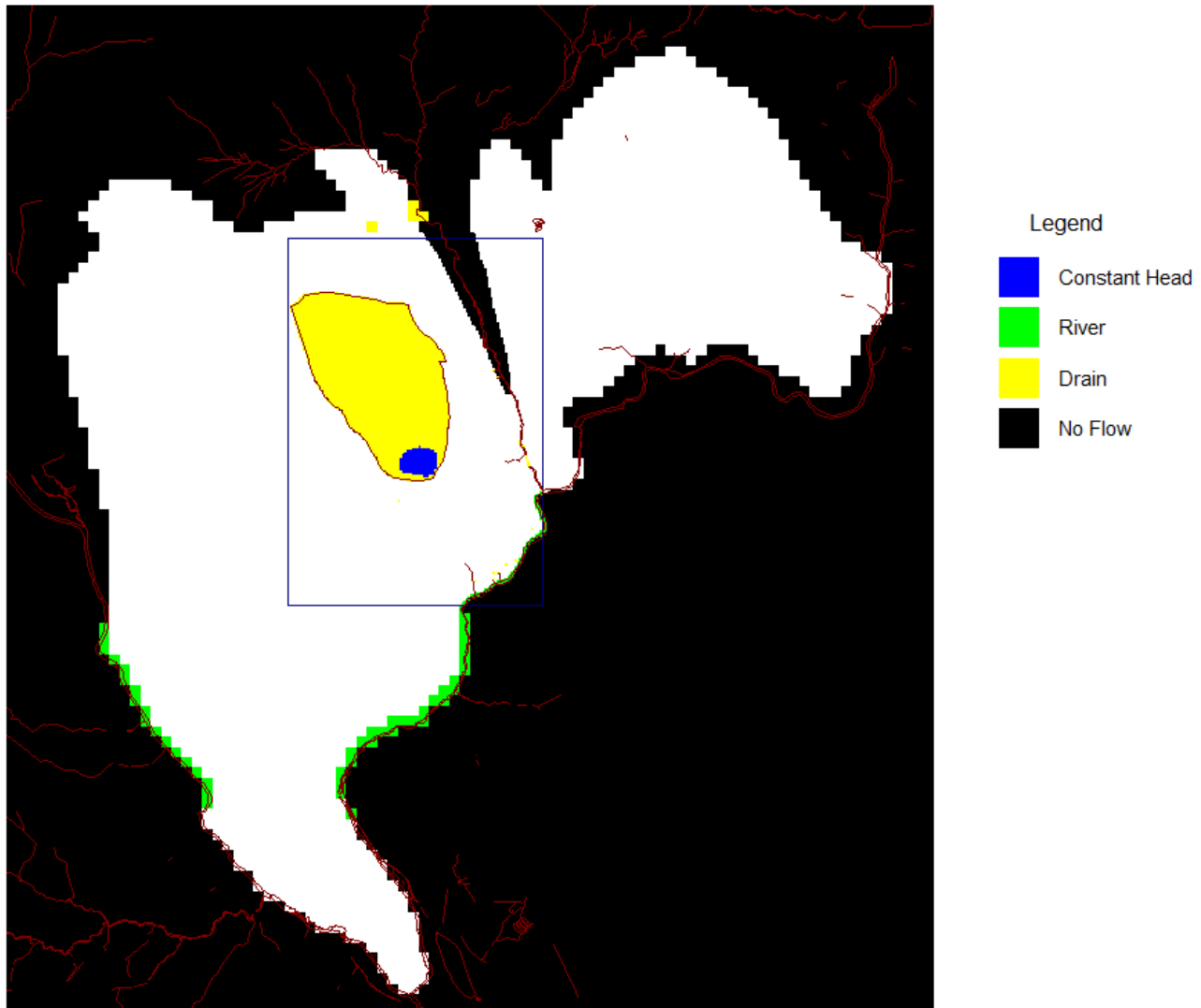
The top surface of Layer 2 (Dowlais Limestone) and the bottom surface of Layer 1 was modified in the vicinity of the proposed Quarry extension as shown on Figure 3.1. The outline of the Quarry extension to the north of the current Site can be clearly seen.

Figure 3.1 Proposed extension: top elevation Layer 2



As with the calibrated models, drain cell boundary conditions were then applied within the whole of the proposed extension area. The drain cell head was set at ground level, i.e. the proposed quarry base. As with the calibrated models, the drain cell hydraulic conductivity was set at 0.3 m/d. This is higher than the aquifer hydraulic conductivity and thus these cells provide little resistance to groundwater discharge. These cells were assigned to Reach 3 (Figure 3.2).

Figure 3.2 Drain and constant head boundary conditions applied within the proposed extension area



The groundwater flux predicted to discharge to the quarry base in Reach 3 was re-introduced into the model via the proposed infiltration pond using the same methodology as described in Section 2.2.5. The proposed pond is shown on Figure 3.2. It is understood that the ground level will not be significantly altered in the vicinity of the proposed infiltration pond and that a water level in the pond of around 270 mAOD is expected to develop. Given that the eastern infiltration pond in the calibrated model was adjusted upwards to 275 mAOD to allow for calibration residuals, a head of 275 mAOD was also applied to the proposed recharge pond in the prediction model. Applying a correction for calibration residuals is not considered significant, as the purpose of the model is to demonstrate that southward flux to the Cwm Taf Fechan springs would be preserved by maintaining the heads around the infiltration pond between the calibration and prediction conditions (i.e. it is the relative level change between runs which is important not the absolute levels).

3.2 Model Results

3.2.1 Predicted heads

Predicted heads for the higher hydraulic conductivity model are shown on Figure 3.3 and for the lower hydraulic conductivity model in Figure 3.4. Both variants show a significant lowering of the head in the vicinity of the proposed quarry area (groundwater contours are inflected northwards) with a more significant drawdown in the model with the lower hydraulic conductivity as the surrounding heads are higher.

As the quarrying operation takes most of the Dowlais Limestone, Layer 2 becomes thin in the proposed quarry area and the groundwater head falls below the base for a significant part of the north-western proposed quarry area (purple cells).

The effect of the infiltration pond can clearly be seen with both the models. For the higher hydraulic conductivity model, Figure 3.3 shows the head rising above 270 mAOD in the vicinity of the pond. In the lower hydraulic conductivity model, the heads are also raised in the vicinity of the pond (the small area within the contour line immediately to the northwest of the pond is lower than 270 mAOD).

South of the proposed infiltration pond, groundwater flow largely resumes its southerly flow direction, towards the Taf Fechan River and associated springs.

Figure 3.3 Proposed restoration: modelled heads in Layer 2: hydraulic conductivity 0.25 m/d

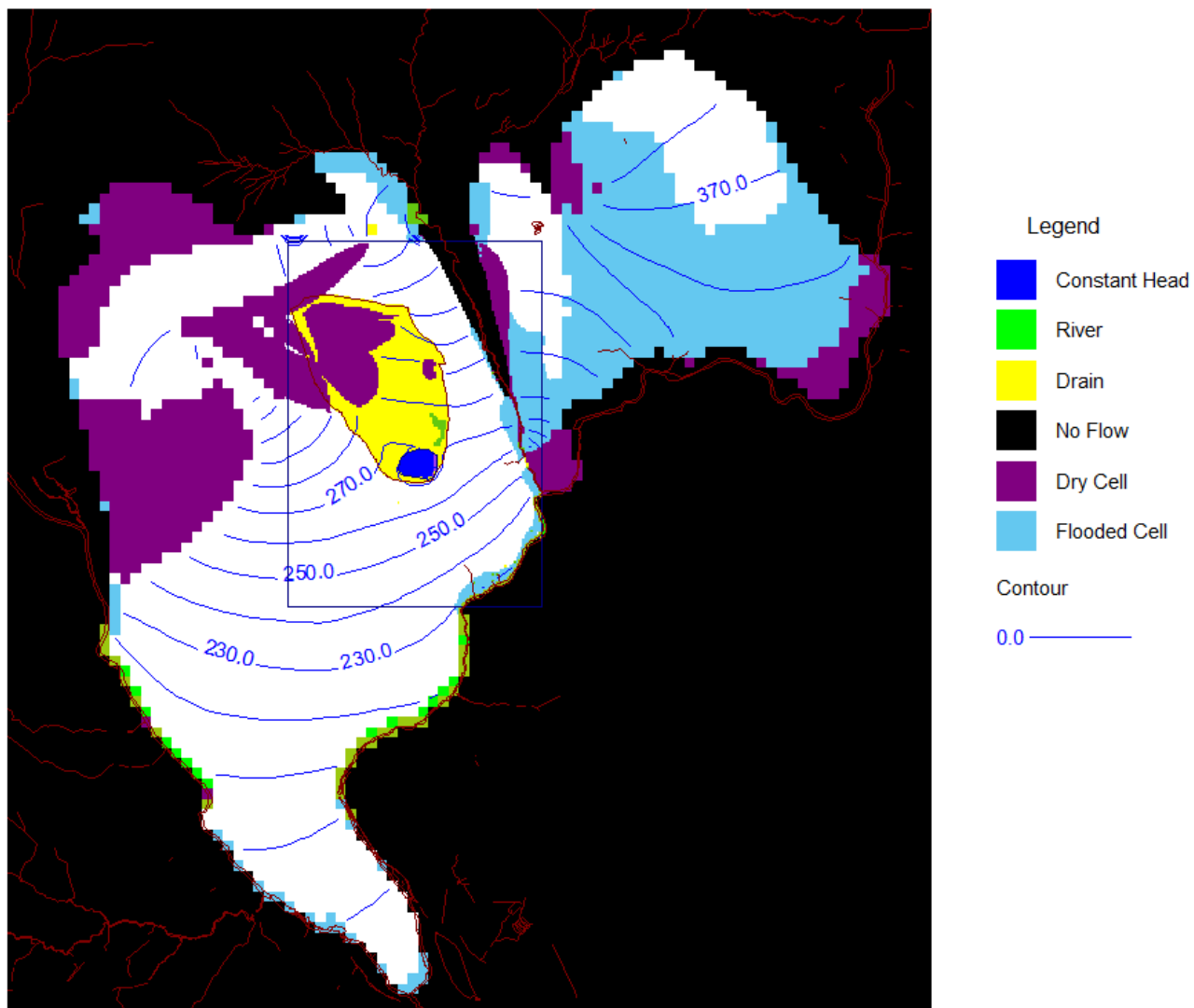


Figure 3.4 Proposed restoration: modelled heads in Layer 2: hydraulic conductivity 0.15 m/d

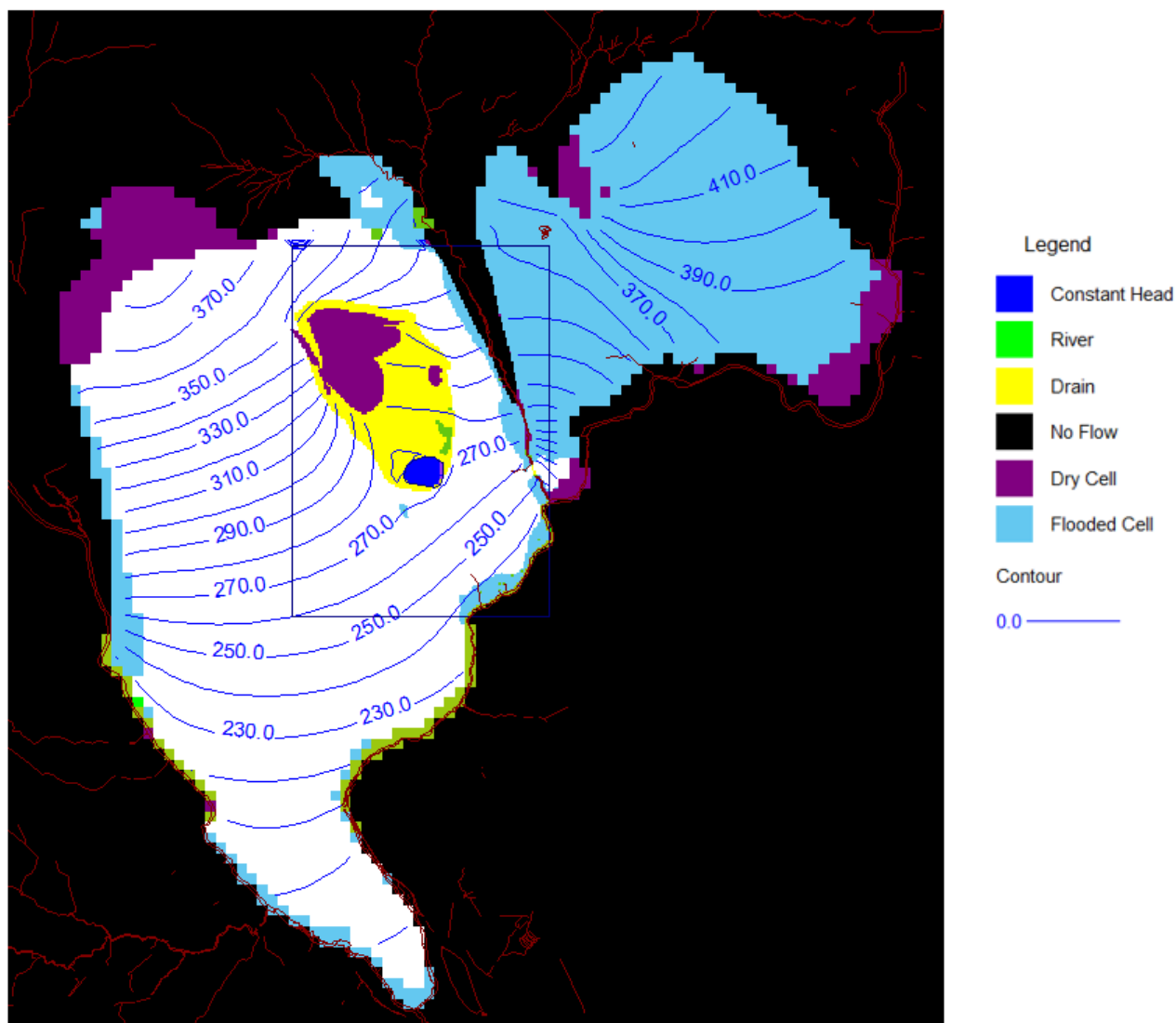


Figure 3.5 and Figure 3.6 show the additional groundwater drawdown from the proposed quarry extension. These figures have been generated by subtracting the heads in the prediction model from the heads in the calibrated model. The greatest difference is within the Site itself, in the north-western part where the Dowlais Limestone becomes fully dewatered. Whilst the figures show a reduction in water level due to the quarry extension extending a significant distance to the south of the site, we note that it is the water balance that provides the key evidence as to the likely impact on spring and river flows.

**Figure 3.5 Additional drawdown imposed by proposed quarry extension in Layer 2:
hydraulic conductivity 0.25 m/d**

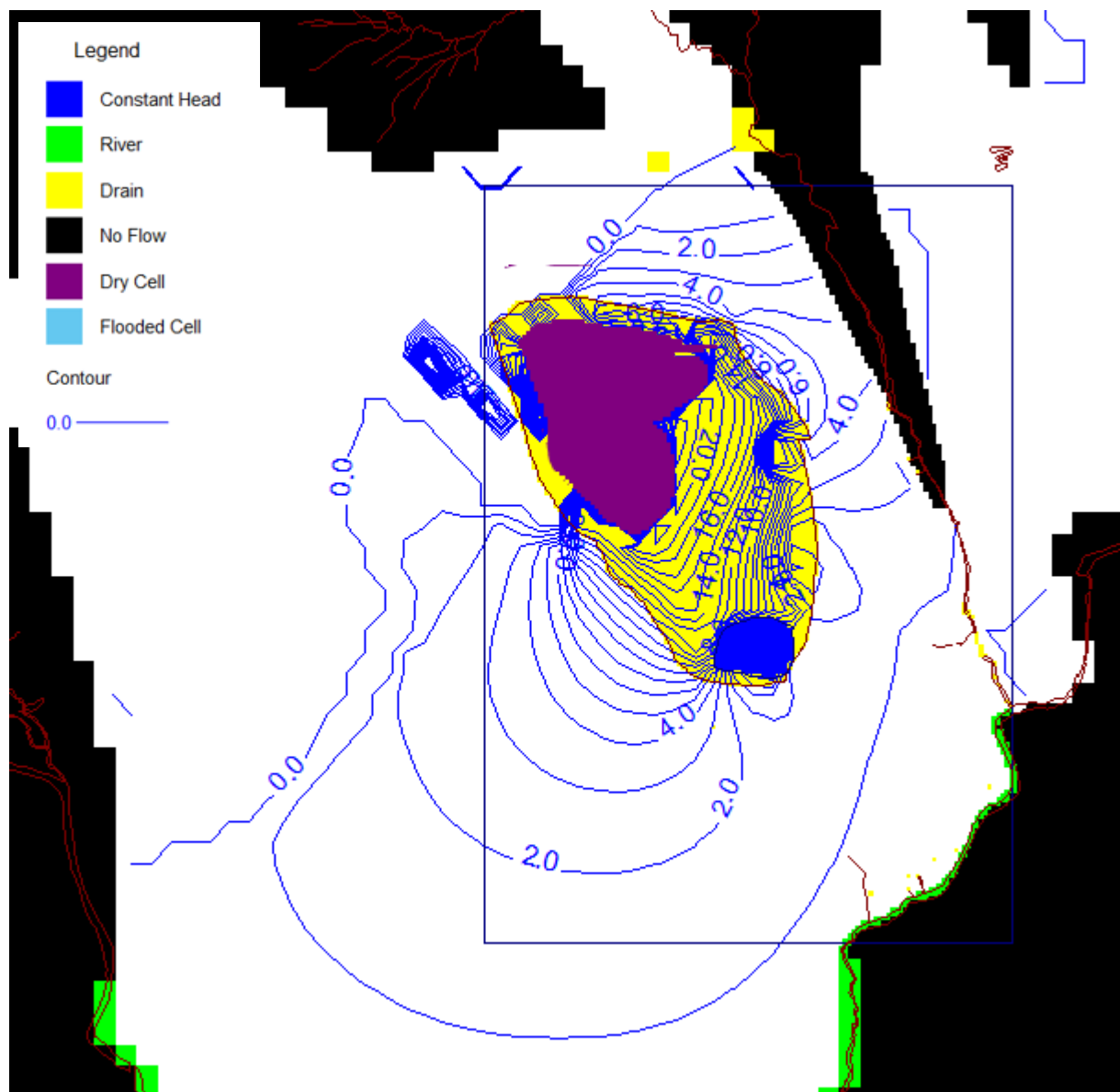
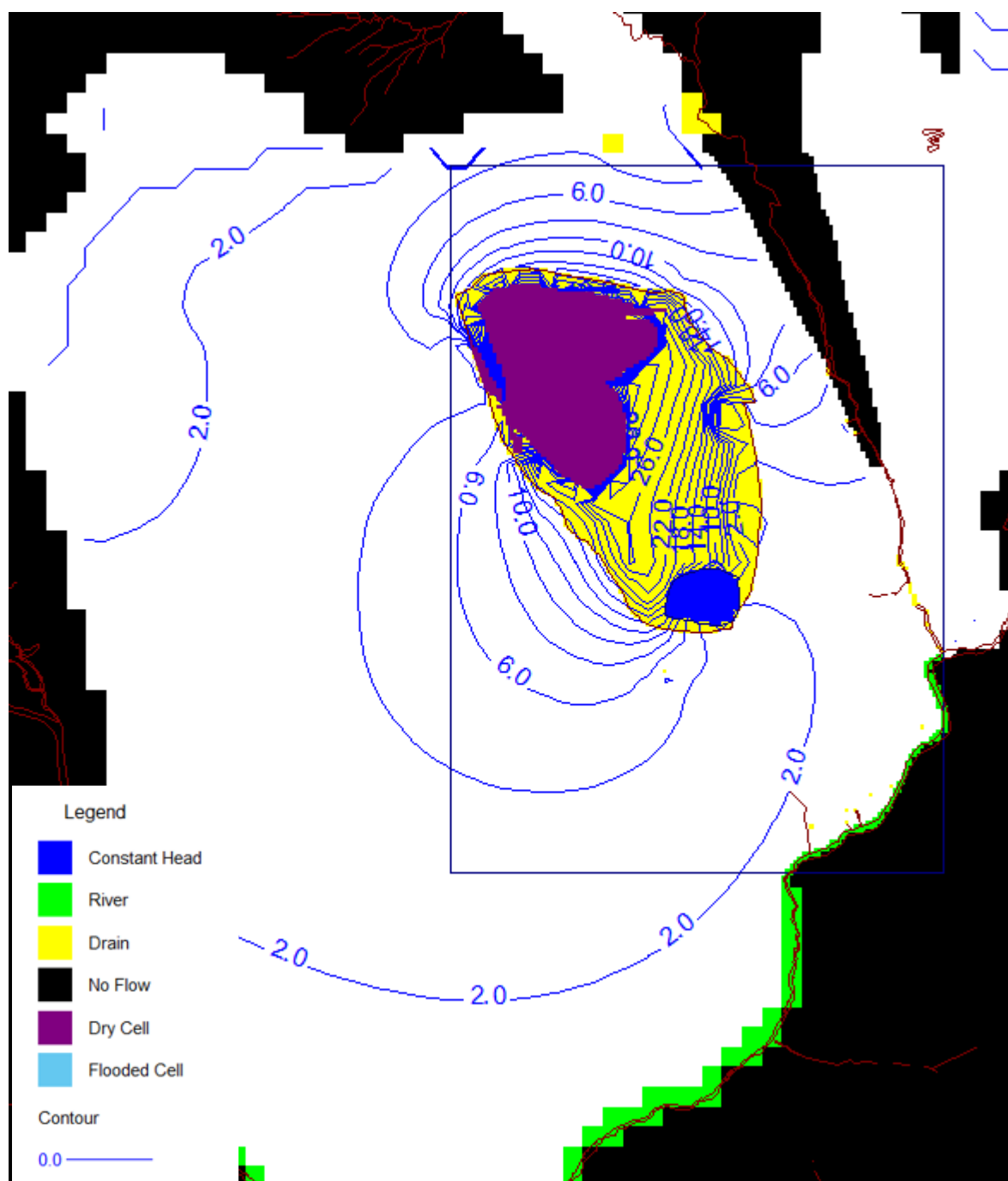


Figure 3.6 Additional drawdown imposed by proposed quarry extension in Layer 2: hydraulic conductivity 0.15 m/d



3.2.2 Water balance

The water balance for the model with the higher limestone hydraulic conductivity (0.25 m/d) is presented in Table 3.1 and for the lower hydraulic conductivity (0.15 m/d) in Table 3.2. The model with the higher hydraulic conductivity has a higher discharge to the drain and river cells. This is because there is proportionally more water in the higher hydraulic conductivity model being captured by the Quarry springs which is being re-introduced via the infiltration pond (constant head boundary) and this water must discharge at the down hydraulic gradient boundaries.

Table 3.1 Model water balance: hydraulic conductivity 0.25 m/d

Description	Inflow (m ³ /d)	Outflow (m ³ /d)
Recharge	5.94E+03	0.00E+00
Constant head	1.42E+03	4.17E-03
River	0.00E+00	4.52E+03
Drain	0.00E+00	2.83E+03
TOTAL	7.36E+03	7.36E+03
ERROR	-1.31E-04	

Table 3.2 Model water balance: hydraulic conductivity 0.15 m/d

Description	Inflow (m ³ /d)	Outflow (m ³ /d)
Recharge	5.94E+03	0.00E+00
Constant head	9.10E+02	2.49E-01
River	0.00E+00	4.13E+03
Drain	0.00E+00	2.73E+03
TOTAL	6.85E+03	6.85E+03
ERROR	4.70E-06	

The river fluxes by reach for the higher hydraulic conductivity model are presented in Table 3.3 and for the lower hydraulic conductivity run in Table 3.4. In these tables the calibrated model fluxes and the percentage difference between calibrated and prediction model are also shown. The prediction model shows a small decrease in the discharge to both the Taf Fawr and Taf Fechan. This is due to the losses from the model to the quarry void as there is more water lost from the model drain cells than is re-introduced at the infiltration pond. This would not occur in reality unless excess water was discharged from the pond overland. The lower hydraulic conductivity model has a large net reduction compared to the higher hydraulic conductivity model.

Table 3.3 River boundary fluxes by reach: hydraulic conductivity 0.25 m/d

Watercourse	Layer	Reach	Calibrated model river flux (m ³ /d)	Prediction model river flux (m ³ /d)	Percentage difference
Taf Fawr	1	1	-692	-684	-1.18
Taf Fawr	2	2	-563	-547	-2.88
Taf Fawr	3	3	-49	-48	-2.79
Taf Fawr	4	4	-459	-457	-0.49
Taf Fawr Total			-1,763	-1,735	-1.59
Taf Fechan	1	5	-221	-218.15	-1.29
Taf Fechan	1/2	6	-878	-848.31	-3.38

Taf Fechan	2	7	-494	-471.58	-4.54
Taf Fechan	3	8	-1.0	-1.12	11.70
Taf Fechan	4	9	-17	-16.72	-1.66
Taf Fechan	4	10	-934	-933.07	-0.10
Taf Fechan	3/4	11	-301	-300.97	-0.01
Taf Fechan Total			-2,846	-2,790	-1.97

Note: negative values represent flows out of the model domain i.e. groundwater discharge to rivers. Negative percentage difference represents reduction in flow in predicted model compared to calibrated model.

Table 3.4 River boundary fluxes by reach: hydraulic conductivity 0.15 m/d

Watercourse	Layer	Reach	Calibrated model river flux (m ³ /d)	Prediction model river flux (m ³ /d)	Percentage difference
Taf Fawr	1	1	-602	-588	-2.34
Taf Fawr	2	2	-649	-620	-4.45
Taf Fawr	3	3	-50	-49	-2.75
Taf Fawr	4	4	-329	-320	-2.83
Taf Fawr Total			-1,630	-1,576	-3.29
Taf Fechan	1	5	-208	-203.2	-2.30
Taf Fechan	1/2	6	-824	-781.0	-5.21
Taf Fechan	2	7	-415	-386.5	-6.88
Taf Fechan	3	8	-1.0	-1.3	29.12
Taf Fechan	4	9	-21	-20.1	-4.47
Taf Fechan	4	10	-829	-827.4	-0.20
Taf Fechan	3/4	11	-330	-330.2	0.06
Taf Fechan Total			-2,628	-2,550	-2.98

Note: negative values represent flows out of the model domain i.e. groundwater discharge to rivers

The spring flows by reach for the higher hydraulic conductivity model are presented in Table 3.5 and for the lower hydraulic conductivity run in Table 3.6. The large increase in discharge to the quarry base can be clearly seen in these tables. The higher hydraulic conductivity model has the higher percentage difference. This is because the workings have now dropped significantly below the regional water table in the northern parts of the Quarry and the higher hydraulic conductivity allows more groundwater to be discharged.

These discharges to the quarry are compensated for by the infiltration pond. Both prediction models also show a significant increase in groundwater recharge from the infiltration pond.

The higher hydraulic conductivity model shows a 16% reduction in discharge to the Taf Fechan springs and the lower hydraulic conductivity model a 15% reduction. However, as noted in Section

2.3.3.3, the model probably does not accurately represent these spring flows and the total groundwater discharge to the Taf Fechan River in Reach 7 is probably a better measure of groundwater discharge to surface water at this location. The models show a 5 to 8% reduction in flow to Reach 7 of the Taf Fechan River and the Taf Fechan springs between the calibrated and prediction models.

The model also shows a small reduction in discharge to the Nant y Glais River of between 3 and 8%.

Table 3.5 Spring flows: hydraulic conductivity 0.25 m/d

Spring group	Layer	Reach	Calibrated model drain flux (m ³ /d)	Predicted model drain flux (m ³ /d)	Percentage difference
Nant y Glais springs (including Blaenglais Spring)	1 & 4	1	-15.18	-10.59	-30.26%
Cwm Taf Fechan springs	2	2	-36.17	-30.38	-16.00%
Quarry base - western limb	2	3	0.00		
Quarry base - eastern limb	2	4	-576.19		
Quarry base – total	2	3 & 4	-576.19	-1,655.51	187.32%
Infiltration pond - western limb	2	1	0.00		
Infiltration pond - eastern limb	2	2	456.23		
Infiltration pond - total	2	1 & 2	456.23	1,419.54	211.14%
Nant y Glais river	2	5	-210.38	-199.81	-5.02%
Nant y Glais river	3	6	-5.09	-5.01	-1.48%
Nant y Glais river	4	7	-954.08	-931.97	-2.32%
Nant y Glais river total			-1,170	-1,137	-2.80%
Quarry Processing Area	2	8	0.00	0.00	0.00%

Note: negative values represent flows out of the model domain i.e. groundwater discharge to springs

Table 3.6 Spring flows: hydraulic conductivity 0.15 m/d

Spring group	Layer	Reach	Calibrated model drain flux (m ³ /d)	Predicted model drain flux (m ³ /d)	Percentage difference
Nant y Glais springs (including Blaenglais Spring)	1 & 4	1	-15.33	-10.77	-29.74%
Cwm Taf Fechan springs	2	2	-52.85	-45.00	-14.86%
Quarry base - western limb	2	3	-130.79		
Quarry base - eastern limb	2	4	-541.2		
Quarry base – total	2	3 & 4	-671.99	-1,586.46	136.08%
Infiltration pond - western limb	2	1	53.99		

Infiltration pond - eastern limb	2	2	223.1		
Infiltration pond - total	2	1 & 2	277.09	909.95	228.40%
Nant y Glais river	2	5	-207.96	-175.25	-15.73%
Nant y Glais river	3	6	-6.02	-5.87	-2.47%
Nant y Glais river	4	7	-962.95	-892.69	-7.30%
Nant y Glais river total			-1,177	-1,074	-8.76%
Quarry Processing Area	2	8	-55.74	-10.97	-80.33%

4 Conclusions

Vaynor Quarry is located within Limestone strata where groundwater flow is largely governed by the frequency, orientation and transmissivity of fissures. Contouring of the Site groundwater levels as presented in Figures 9.13 and 9.14 of the HIA (Stantec, 2020) suggests that fissures are well connected, and that groundwater flow approximates to a continuous flow domain. On this basis, it was considered appropriate to represent the Site conceptualisation within a porous medium flow model.

Construction of the porous medium flow model showed that the head distribution from the Site groundwater levels is more complex and that a satisfactory calibration could not be achieved using a simple representation of each stratum with a single hydraulic conductivity value and a single recharge value across the model domain. It is possible that an improved calibration could be achieved by introducing additional hydraulic conductivity and / or recharge zones, but there is insufficient data available to justify this approach. It is also noted that there is insufficient data available on the fissure frequency, orientation and transmissivity to justify an alternative modelling approach that would be more suited to modelling a fissure flow system.

Modelling the system was further complicated by the steep topography in the vicinity of the Site which resulted in the model layers requiring variable thicknesses and cropping out on valley sides. This geometry is challenging for the solvers used in the porous medium flow model used for this study.

The best model calibration was obtained using a relatively low hydraulic conductivity for limestone strata of between 0.15 and 0.25 m/d. This represents the weighted average hydraulic conductivity of the fissures and limestone matrix. In reality the fissures are likely to have a higher hydraulic conductivity and the matrix a lower hydraulic conductivity.

Overall, the model simulated groundwater flow from the Site to the south towards the Taf Fachan and Taf Fawr Rivers, and this is consistent with field observation. Little flow is simulated towards the Nant y Glais, but this is largely a function of the selection of model boundary conditions (drain cells representing observed spring discharges).

The model results suggest that there is limited groundwater discharge to the quarry base. Discharge is greater in the eastern quarry limb compared to the western limb. However, it is noted that as the model does not represent observed groundwater levels at the Site accurately, this may not be representative of actual conditions. It is also possible that spring discharges at the Site are from perched water, which would not be simulated in the model. The water that is discharged is reintroduced to the aquifer at the infiltration ponds.

A prediction model has been run with the proposed quarry simulated. The proposed quarry extends further to the north. As the Dowlais Limestone hydraulic gradient increases to the north, the saturated thickness adjacent to the quarry increases northwards. Thus, it is likely that higher groundwater discharges to the quarry base will occur under the proposed quarry. This water will drain southwards down the topographic gradient that will be maintained on the quarry floor to a new and larger infiltration pond located at the southern end of the quarry. This pond will be located approximately across hydraulic gradient from the current eastern infiltration pond. It is assumed that the elevation of this pond will be the same as the current eastern pond and that groundwater that has discharged into the quarry will be re-introduced to the aquifer at this location.

The model suggests that the regional groundwater flow direction under the proposed quarry extension will be similar to that occurring at present and that groundwater discharge will continue to the Taf Fechan and Taf Tawr Rivers and associated springs.

The model suggests a modest reduction in groundwater discharge to these rivers and flows as the volume of water discharging at the quarry base is larger than is being re-introduced via the infiltration pond. There is also a reduction in flow to the Taf Fechan springs, but the modelled magnitude of these discharges is small compared to the modelled discharge to the rivers. In reality, there may be some evaporative and other consumptive losses whilst the water is flowing within the quarry and from the infiltration pond itself, but these would be expected to be quite modest.

In reality, the groundwater flow direction and magnitude following recharge at the proposed infiltration pond will depend on the fissures that the pond intersects. On the assumption that some fissures are intersected and recharge to groundwater is possible, it is likely that groundwater flow will be towards the south and the rivers. Overall, it is considered that the net impact of groundwater discharge to the rivers and springs will not be significantly different from under the current situation.

5 References

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