

Newsells Park Winery

Hydraulic conditions for culvert sizing

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1 Introduction

1.1 Background

Newsells Park Winery have recently gained planning permission for a development which consists of: proposed winery production, processing and storage facility including hospitality functions, service apron, car park, access road, wetland waste treatment solution and landscaping. The location of the site is Newsells Park Winery, Whiteley Hill, Barkway, Royston, Hertfordshire, SG8 8DY.

The Lead Local Flood Authority (LLFA) highlighted that there is a surface water flow path that intersects the new access road and the surface water flood map shows this (Figure 1.1). Newsells Park Winery proposes to raise the road level above flood levels and install a culvert to not impede water flow in this location in order to maintain safe access to and from the development. Newsells Park Winery have appointed HR Wallingford to assess the hydraulic conditions to size the culvert at the access road location.

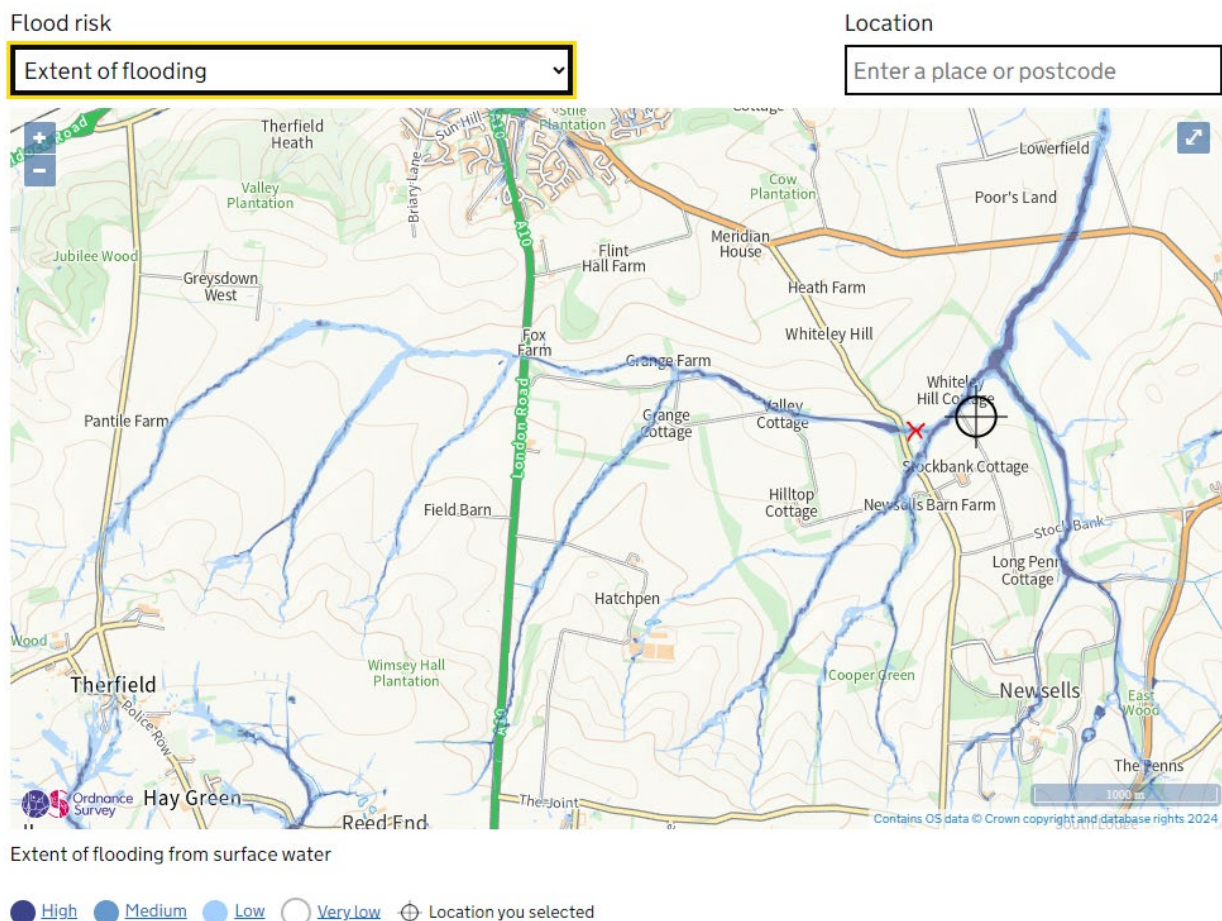


Figure 1.1: Surface water flood map (red cross marks location of access road crossing flow path)

Source: <https://check-long-term-flood-risk.service.gov.uk/map?>

1.2 Scope of work

The following tasks were carried out:

- Hydrology assessment. A hydrological assessment to determine the peak flow rate at the location of the access road crossing;
- Culvert hydraulic design. Hydraulic calculations to assess the size and / or number of culverts under the access road.

2 Hydrology assessment

A hydrological assessment to determine the peak flow rate at the location of the access road crossing. The assessment was undertaken following the Environment Agency's (EA) 2020 guidance and using both the Revitalised Flood Hydrograph rainfall-runoff method (ReFH2.3) and the Flood Estimation Handbook (FEH) statistical methods. The assessment is for the 1 in 100 year (1% Annual Exceedance Probability) event plus climate change.

2.1 Catchments to the site

There are two catchments upstream of the site, as shown in Figure 2.1, that were identified using the FEH webservice. Catchment 1 drains overland across the location of the proposed access road and Catchment 2 is the catchment of the existing stream south of the proposed access road. Catchment 1 upstream of the proposed culvert location is rural and 8.77 km² in area. Catchment 2 upstream of the proposed culvert location is rural and 3.22 km² in area. The total catchment area to the site is 11.99 km². The key catchment descriptors from the FEH webservice required for the hydrological analysis are given in Table 2.1.

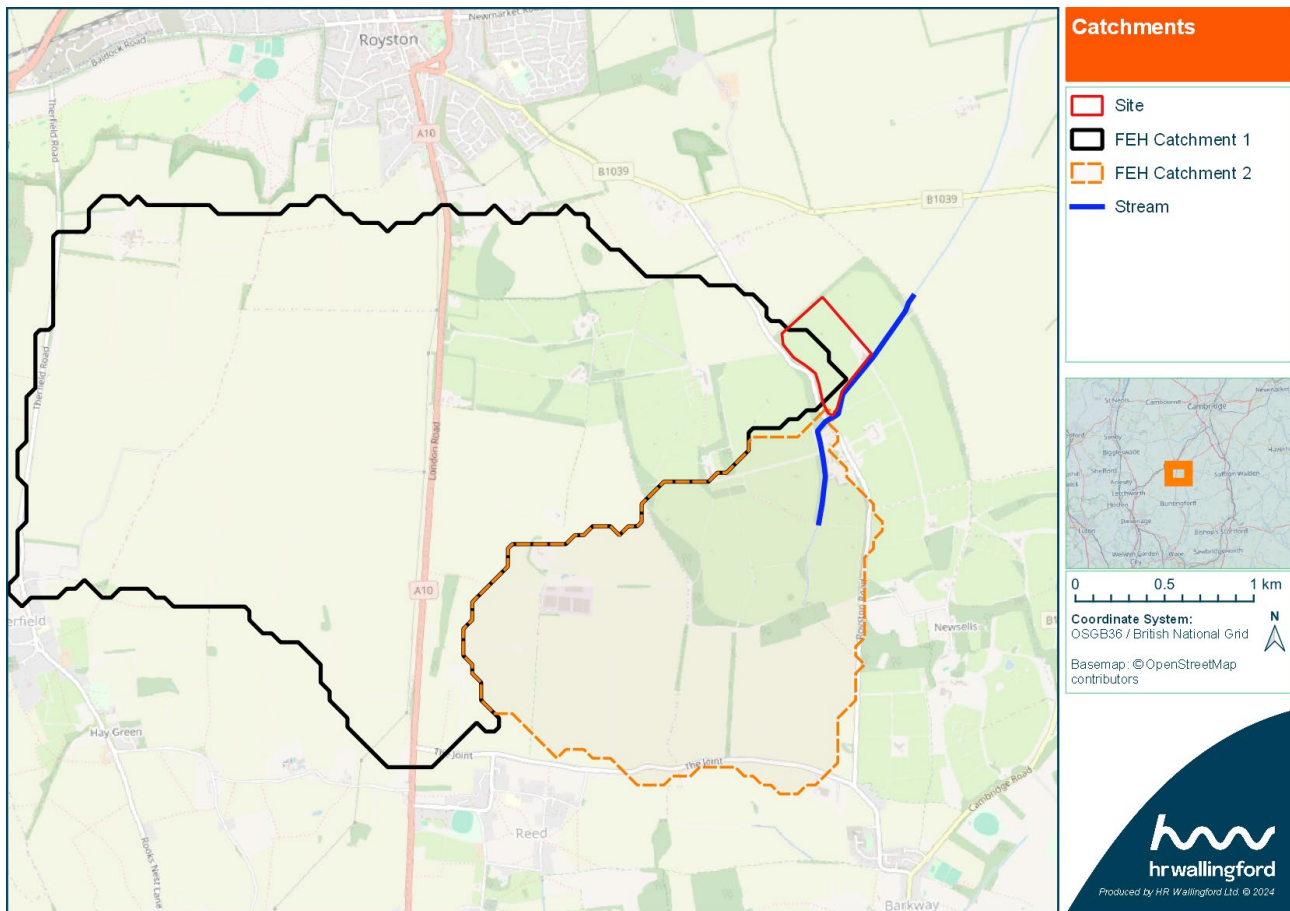


Figure 2.1: Catchments upstream of the site

Table 2.1: Key catchment descriptors

Parameter	Catchment 1	Catchment 2
Area (km ²)	8.77	3.22
Standardised Annual Average Rainfall 1961 to 1990 (mm)	602	610
Average drainage length (km)	3.39	1.7
Average drainage slope (m/km)	46.5	65.9
Longest drainage path (km)	6.2	2.9
BFIHOST	0.943	0.819
SPRHOST (%)	5.9	14.4
PROPWET	0.3	0.3

The catchments parameters relating to runoff from soils (BFIHOST and SPRHOST) identify that the catchment is permeable. Because of the highly permeable nature of the catchment the design flow was estimated using both the statistical method and the rainfall-runoff method. This is because the statistical method is often considered more reliable for permeable catchments, especially compared to an un-calibrated rainfall runoff model (EA, 2020).

2.2 Statistical method

The 1% AEP flow was estimated using the FEH statistical method using WINFAP (an approach to support estimation of peak flows). The first part of the method is to estimate the index flood (known as QMED) which is equivalent to the flood that has a 50% AEP (or on average once every two years). For ungauged catchments this is estimated from catchment descriptors and

adjusted based on nearby gauged catchments. This was estimated as 0.19 m³/s for Catchment 1 and 0.13 m³/s for Catchment 2.

To estimate flows for other frequencies of occurrence, a growth curve was estimated using the pooled approach. This is where observed peak flows from a number of gauged catchments selected based on hydrological similarity is used to fit the statistical distribution. The default pooling group selected by WINFAP was used. The peak flows estimated using the statistical method are given in Table 2.2.

Table 2.2: Peak flows estimated using the FEH statistical method

Annual Exceedance Probability (AEP)	Return period (years)	Catchment 1 peak flow (m ³ /s)	Catchment 2 peak flow (m ³ /s)
50%	2	0.19	0.13
3.33%	30	0.48	0.34
1%	100	0.64	0.47

2.3 Rainfall-Runoff method

The FEH revitalised flood hydrograph rainfall-runoff model (ReFH2.3) was also used to estimate the 1% AEP flood. The model was run for a range of storm durations for the winter and summer storm profiles. The 1% AEP peak flow of 0.86 m³/s was estimated for catchment 1 from the 8.5 hour storm and peak flow of 0.57 m³/s for Catchment 2. The estimates of peak flow for Catchment 1 ranged from 0.69 to 0.86 m³/s depending on the storm duration.

2.4 Choice of design flow

The flow estimated using the statistical method is preferred because the statistical method is generally considered more reliable for permeable catchments, especially compared to an un-calibrated rainfall runoff model (EA, 2020). It is noted that the range in estimate of peak flow for Catchment 1 the rainfall-runoff method was 0.69 to 0.86 m³/s, the lower estimate being similar to the best estimate from the statistical method.

It is recommended that the higher flow from the rainfall-runoff model is used as a sensitivity test.

2.5 Climate change

The climate change allowances were taken from the Defra website for the Cam and Ely Ouse Management Catchment which contains the catchments to the site. The Defra guidance recommends the increase in river flows for catchments greater than 5 km² and that the Central climate change scenario is used. The increase in peak river flow for the Central climate change scenario is 9% in the 2080s. For comparison the increase in peak river flow for the Upper climate change scenario is 45% in the 2080s.

The estimate of the design flow, the 1% AEP plus climate change, for the overland flow from Catchment 1 is 0.70 m³/s and the stream flow south of the site from Catchment 2 is 0.51 m³/s.

3 Culvert hydraulic design

Based on the hydrological assessment an appropriate culvert size and shape will be determined using the CIRIA Culvert, screen and outfall manual (C786).

3.1 Topography

A site topographic survey was provided by the Client which includes elevations on the existing roads and along the route of the proposed access road. In addition, 1 m horizontal resolution Light Detection and Ranging (LiDAR) ground elevation data was downloaded from the Defra survey data website (<https://environment.data.gov.uk/survey>). The ground elevations in the LiDAR compare well to the elevations from the site survey.

The site survey and photographs identify that there is an existing arch culvert on the stream with the smaller catchment (2) that is located south of the proposed access road (Figure 3.1). There are low points and evidence of flow routes across the existing road towards the proposed access road in the photographs and survey (see Figure 3.1).



Figure 3.1: Site survey and photographs showing existing flow routes

Because of the topography and existing overland flow routes (lack of a stream channel) where the flow crosses the proposed access road, a 2D hydraulic model is required to fully assess the effect of the raised road and culverts on flow paths rather than the simplified calculations preferred in the CIRIA Culvert and screen manual (C786).

3.2 Hydraulic model

A small 2D hydraulic model was built to determine the appropriate culvert size required to pass the design flood (1 in 100 year flood plus climate change). The model was constructed using the Infoworks ICM hydrodynamic modelling software, with a flexible mesh developed using terrain sensitive meshing. The average mesh element area was 9 m² with areas of finer mesh defined along the existing road and the proposed access road. The elevations were taken from the 1 m horizontal resolution LiDAR and refined in key areas such as the embankments on the west side of the existing road and the low areas / gaps, which define the flow path across the road set using the site topographic survey.

The dimensions of the existing road culvert on the stream south of the location of the proposed access road were taken from the site topographic survey.

The hydraulic roughness was set to a Mannings n of 0.05 for the open areas of the site to represent grass and 0.025 for the existing road, and for the proposed access road in the with scheme scenario. Model scenarios were created for existing conditions and with the proposed access road and culverts.

3.3 Results for existing conditions

The model for existing conditions was run for the 1% AEP plus climate change flow of 0.70 m³/s from Catchment 1 and 0.51 m³/s from Catchment 2. The model results (Figure 3.2) show that the location of the access road is across the flow path from Catchment 1, but is not influenced by the flow from Catchment 2, which follows the existing stream along lower lying land south of the proposed access road.

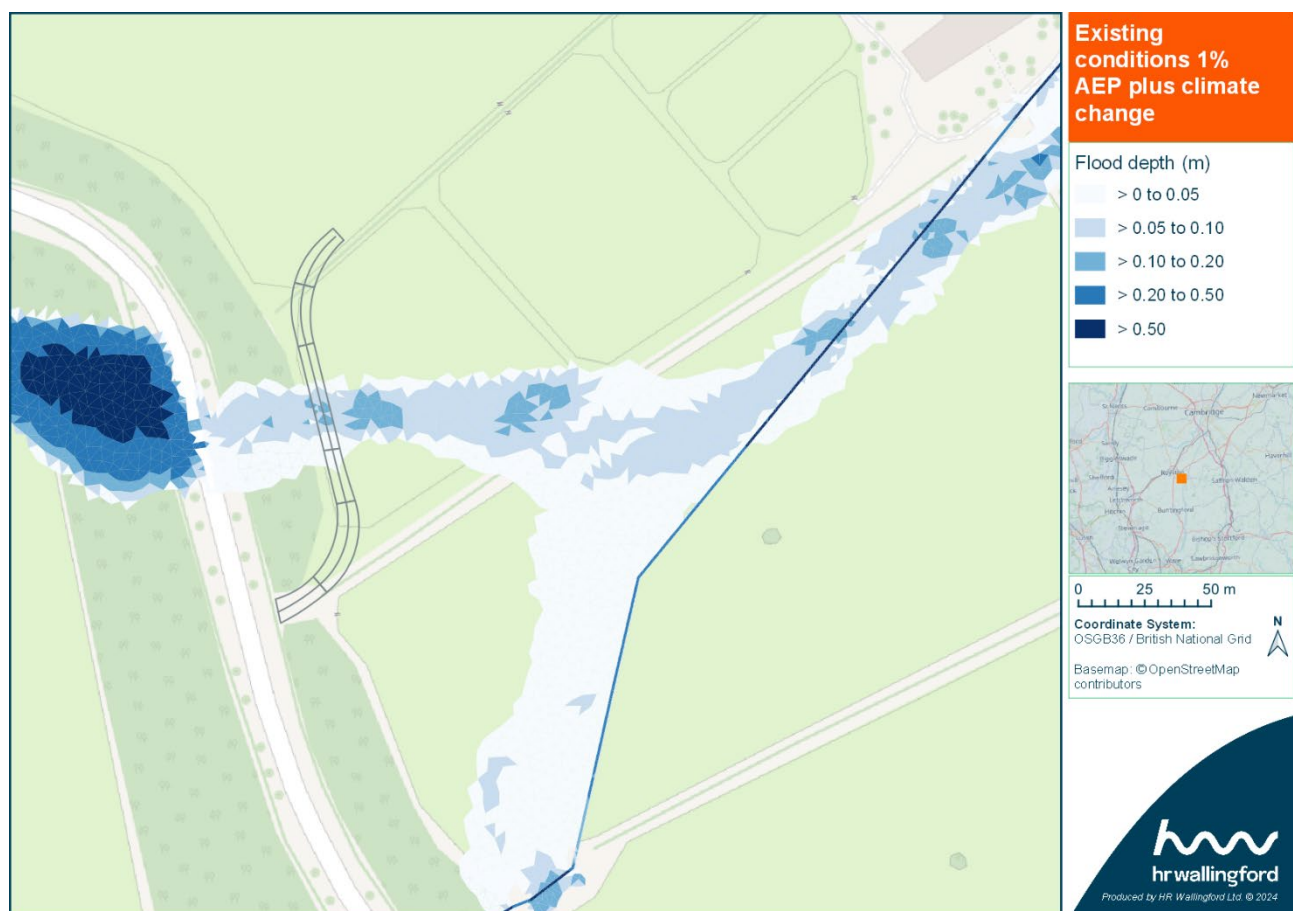


Figure 3.2: Flood depths in existing conditions for the 1% AEP plus climate change event

The peak flood depth at the proposed location of the access road is around 0.15 m and the width of the flow route is approximately 30 m. The width of flow depths greater than 0.1 m is approximately 10 m, and flow depths of less than 0.05 m across a flow width of around 15 m.

3.4 Modelling the proposed access road

The results from the model of existing conditions indicate that the flow depths are relatively low, which makes assessment of culverts more complicated than for a defined stream. To include culverts in the model it was assumed that:

- There would only be minor landscaping modifications of the existing topography, no creation of a ditch or stream;
- The access road would be raised above existing ground elevation across the low lying area that defines the flow path;
- The access road would be at least 300 mm above the top of the culvert(s).

Following the hydraulic design criteria in CIRIA Culvert Manual, the culvert(s) should pass the design flow (1% AEP flow with climate change) under free flow conditions. A number of iterations of the proposed access road were modelled to consider different sizes and number of culverts and the height of the road above ground:

- Rectangular box culverts of the smallest standard size (1 m wide by 0.5 m high) with the road raised 0.8 m above the lowest lying existing ground elevation;
- Pipe culverts of the standard size 300 mm diameter with the access road raised 0.6 m above the lowest lying ground elevation.

The upstream invert level of the culverts has been assumed to be 65.4 m AOD, which is the average ground level on the over land flow route upstream of the proposed access road. The downstream invert level has been assumed to be 65.3 m AOD, which is the average ground level downstream of the proposed access road. The culvert barrel length was set to 5.4 m based on measurements of the width of the proposed access road shown on the Clients site drawings. The slope of the culverts in the model is therefore 0.0185 m/m, which is slightly steeper than the average ground slope of 0.015 m/m.

Inlet parameters

The inlet parameters to estimate inlet losses for the culverts were set using parameters from the CIRIA culvert guide for the culvert shape and assuming headwalls at 0 degrees to the barrel. These are given in Table 3.1.

Table 3.1: Culvert Inlet loss parameters

Inlet Parameter	Rectangular culvert	Circular culvert
Equation type	A	A
K	0.061	0.0098
M	0.75	2
c	0.0423	0.0398
Y	0.82	0.67
Ki	0.7	0.5

Debris screens

The CIRIA Culvert and screen manual (C786) recommends that debris screens are avoided for small culverts because these can increase the chance of blockage. The initial need assessment for a debris screen (Appendix A3 of C786) was completed with the local details of the proposed access road culverts (see Appendix A). This returned a score of 11 which confirms that a debris screen is not required for the culverts.

Model results

The results from the 2D hydraulic model showed that the 1% AEP flow is passed through the proposed access road without overflowing the road surface, with:

- 5 rectangular culverts of 1 m wide by 0.5 m high – it is noted that the culvert height only needs to be 0.3 m for free flow. The water level upstream of the culvert was increased by around 0.14 m compared to existing conditions to a level of 65.66 m AOD. This is a water depth of 0.26 m above the invert of the culvert;
- 4 rectangular culverts of 1 m wide by 0.5 m high – it is noted that the culvert height only needs to be 0.3 m for free flow. The water level upstream of the culvert was increased by around 0.18 m compared to existing conditions to a level of 65.7 m AOD. This is a water depth of 0.30 m above the invert of the culvert;
- 3 rectangular culverts of 1 m wide by 0.5 m high – the water level upstream of the culvert was increased by around 0.23 m compared to existing conditions to a level of 65.75 m AOD. This is a water depth of 0.35 m above the invert of the culvert;
- 15 circular 0.3 m diameter culverts. The water level upstream of the culvert was increased by around 0.16 m compared to existing conditions to a level of 65.66 m AOD. This is a water depth of 0.26 m above the invert of the culvert;
- 8 circular 0.3 m diameter culverts. The water level upstream of the culvert was increased by around 0.33 m compared to existing conditions to a level of 65.85 m AOD. This is a water depth of 0.45 m above the invert of the culvert, which represents considerable headloss as flow enters the culverts. The culvert barrels are still in free flow conditions. The water level upstream of the proposed access road is close to the lowest level of the road at the southern end of the road.

The water level profile from the existing road to the stream is shown in Figure 3.3 and Figure 3.4 and the water levels along the upstream face of the proposed access road in Figure 3.5. These show that water levels upstream of the proposed access road are increased compared to existing conditions for all combinations tested. The greatest increase of around 0.33 m is with the 8 circular 0.3 m diameter culverts because this combination has the smallest opening width and area.

The impact of the culvert on flood depths is shown in Figure 3.6 for a set of 4 rectangular culverts of 1 m by 0.5 m and in Figure 3.7 for a set of 8 circular 0.3 m diameter culverts. This shows that with fewer smaller culvert openings the flood depth upstream of the proposed access road is considerably higher.

The model with 4 rectangular culverts was also run with the Upper climate change scenario. This produced water levels upstream of the proposed access road of 65.75 m AOD, the same as with 3 culverts with the Central climate change scenario.

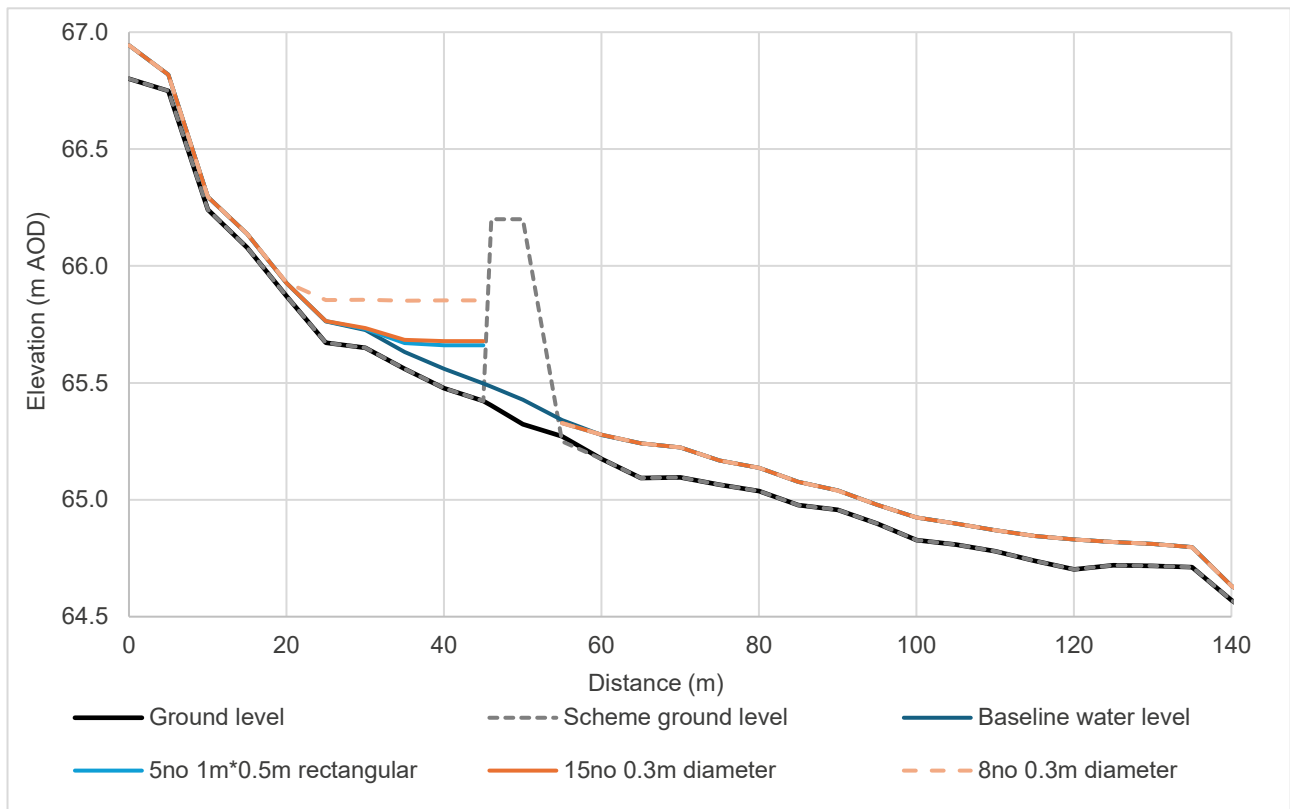


Figure 3.3: Water level profile for a selection of culverts

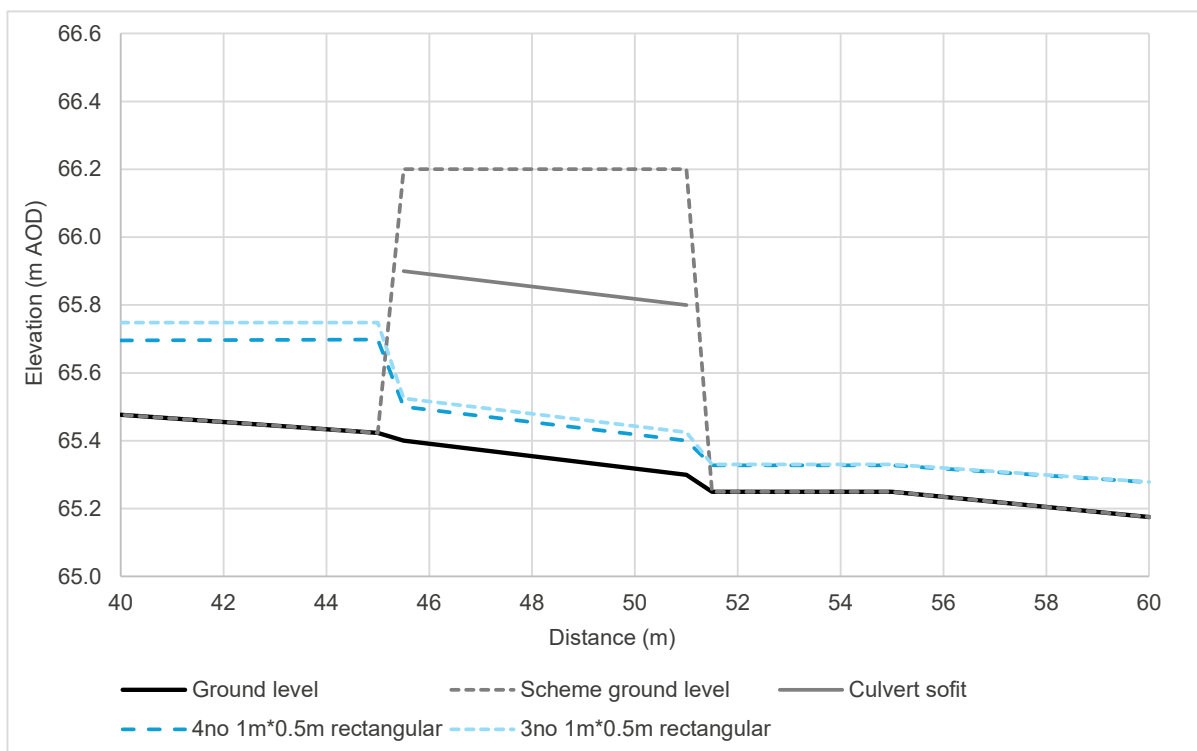


Figure 3.4: Long profile through the proposed access road with fewer rectangular culverts

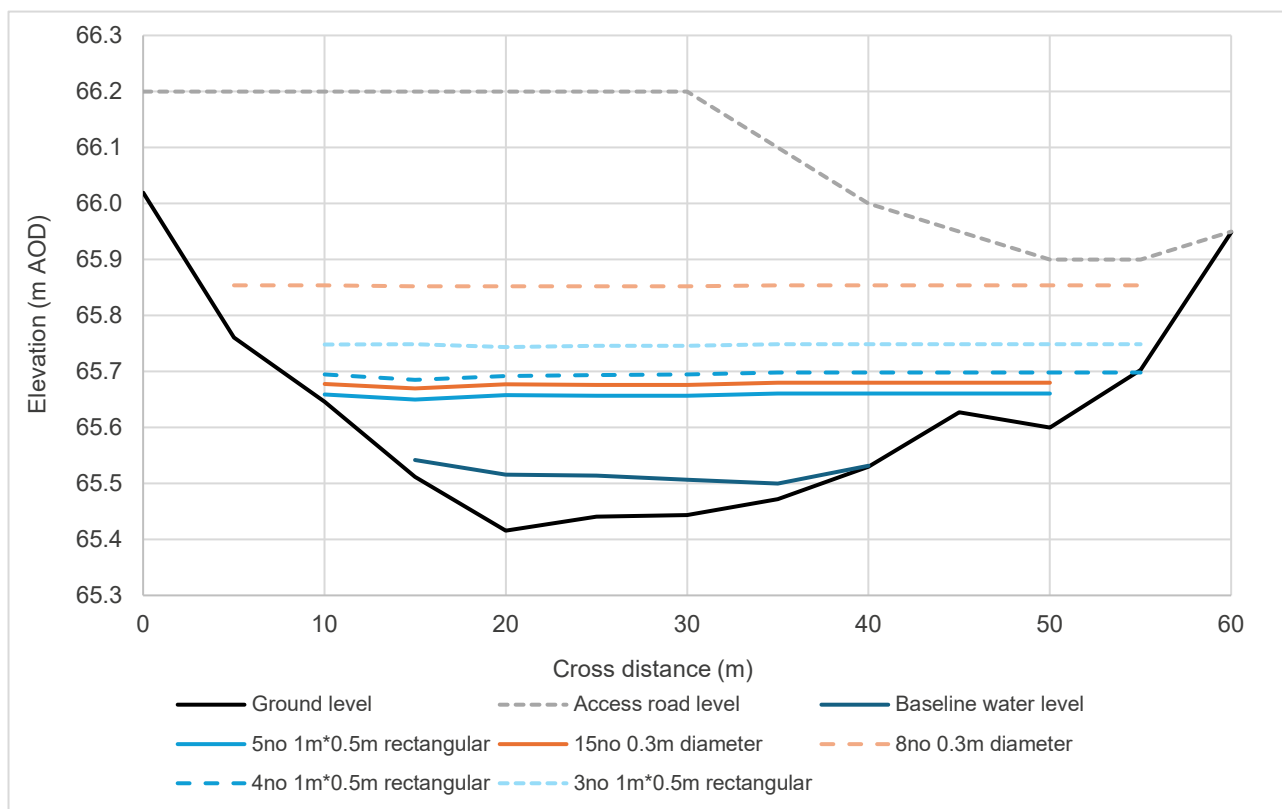


Figure 3.5: Water levels along the upstream face of the proposed access road

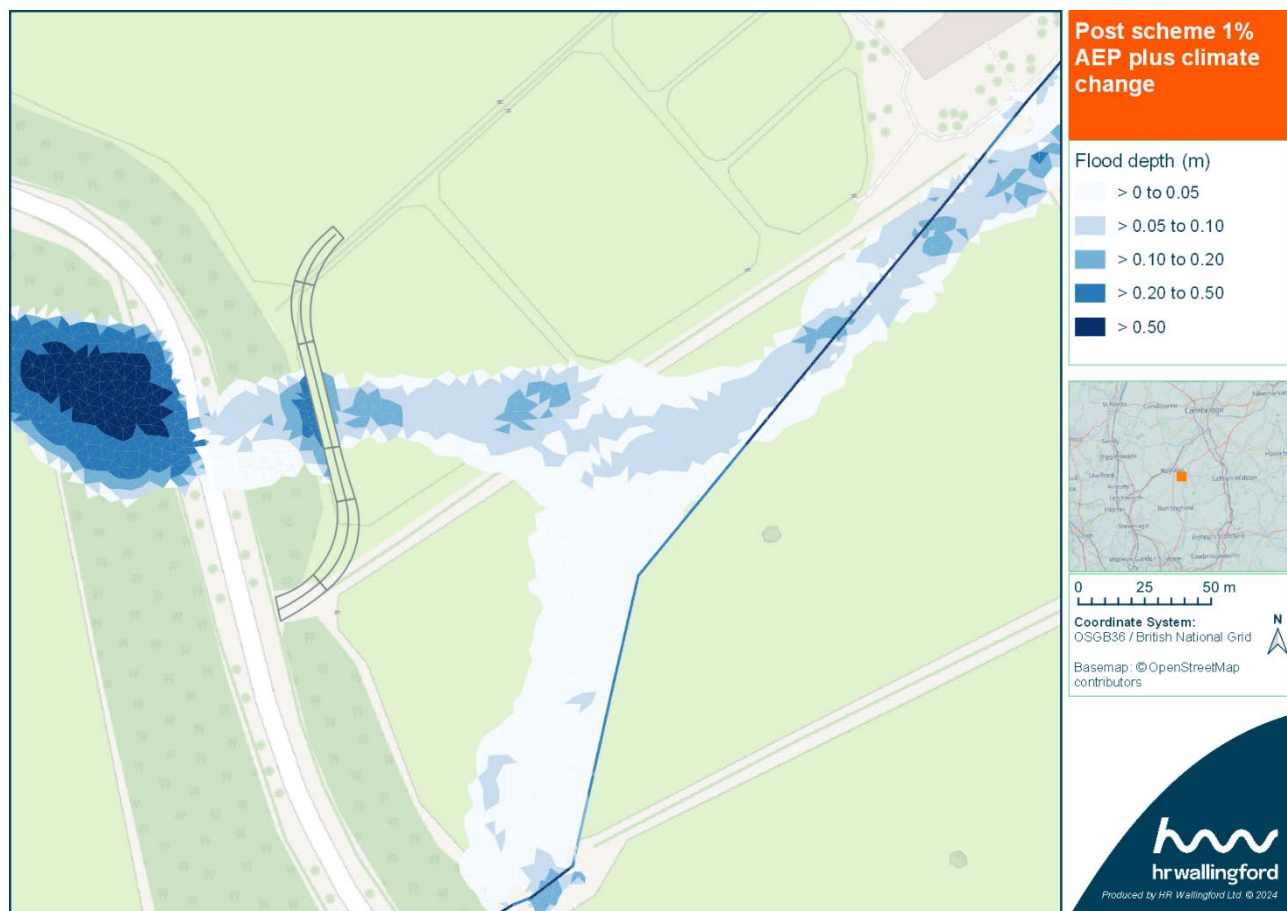


Figure 3.6: Flood depths with a set of 4 rectangular culverts for the 1% AEP plus climate change event

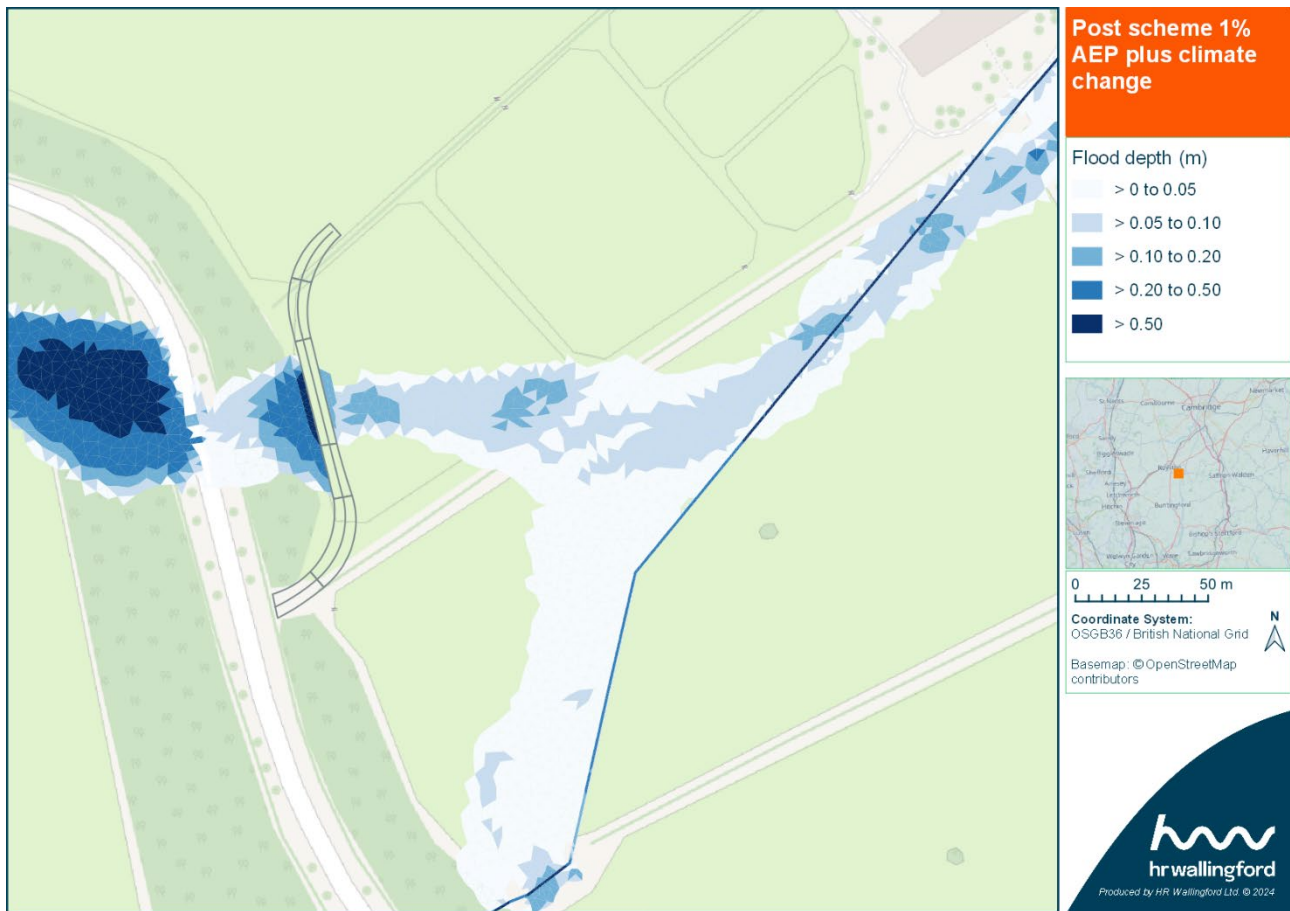


Figure 3.7: Flood depths with a set of 8 circular culverts for the 1% AEP plus climate change event

4 Summary

The 1% AEP design flow with climate change was estimated to be $0.70 \text{ m}^3/\text{s}$ for the catchment draining to the proposed access road. There is not an existing stream at this location and flow would occur as overland flow. There are past flow routes across the existing road identified in site photographs and topographic survey.

The flows were run in a local scale 2D hydraulic model to simulate the flood depths with the site under existing conditions. This identified that the natural flow route across the location of the proposed access road is around 30 m wide with water depths of up to 0.2 m and flow speeds of up to 0.3 m/s.

A range of culvert shapes and dimensions were tested using the 2D hydraulic model. The model showed small differences in the upstream water level with the following combinations:

- 5 rectangular culverts of 1 m wide by 0.5 m high;
- 4 rectangular culverts of 1 m wide by 0.5 m high;
- 15 circular 0.3 m diameter culverts.

The model with 3 rectangular culverts of 1 m wide by 0.5 m high increased water level upstream of the culvert by 0.1 m compared to with 5 culverts and around 0.05 m compared to with 4 culverts.

The model with 8 circular 0.3 m diameter culverts resulted in significantly higher water levels upstream of the proposed road. The water level is close to the lowest point on the proposed

access road at the southern end. If circular culverts were to be installed it is recommended that the diameter should be increased to around 0.5 m to reduce the risk of blockage during a storm.

From a hydraulics and flow capacity point of view a greater number of culvert openings and larger widths increase the free flow capacity. This reduces the risk of the proposed access road overflowing should some of the openings become blocked during a flood.

It is therefore recommended that 4 rectangular culverts of 1 m wide by 0.5 m high are included under the proposed access road.

5 References

1. CIRIA (2019), Culvert, screen and outfall manual C786.
2. Environment Agency (2020), Technical guidance 197_08 Flood Estimation Guidelines. Version 5, June 2020.

Appendices

A Initial need assessment for a debris screen

CIRIA C786 Culvert, screen and outfall manual

Appendix A3 Initial need assessment for a debris screen

Version 1: December 2019

Name of culvert or outfall:	New access road
Location of culvert or outfall:	Newsells winery
Person completing this initial assessment:	Mark Davison
Date of assessment:	04 March 2024

1 Initial debris screen need score (IDSNS)

Main factor (blockage risk source)	Evidence/sub-factor (choose all that are applicable)	Potential score	Applicable?	Score	Comments
A - Potential for debris collection at the inlet -					
When flow is aligned to the centreline of the culvert there will be a smoother contraction and acceleration of flow into the culvert barrel and fewer eddies or areas of low velocity which would tend to hold debris at the inlet.	A1. Flow approach is parallel to the culvert centreline	1	Yes	1	
	A2. Wing walls at inlet that guide flow smoothly into the culvert barrel	2	No		
	A3. Flow approach is skewed relative to the culvert centreline (less than 20 degrees)	3	No		
	A4. Culvert headwall is at right angles to the flow	4	No		
	A5. Flow approach is skewed relative to the culvert centreline (more than 20 degrees)	5	No		
	A6. Additional evidence (potential score between 1 and 5)		No		User can input additional evidence categories and their suggested potential score
	Maximum score for Factor A:	5		Column maximum A	1
B - Potential for debris collection at inlet / culvert size					
The size of a culvert barrel can be a factor in the chance of it becoming blocked with debris, especially from medium-sized debris such as pallets and supermarket trolleys	B1. Culvert barrel greater than 3 m in width and/or greater than 2 m in height	1	No		
	B2. Culvert barrel is between 1.5 m to 3 m in width and/or between 1 m to 3 m in height	5	No		
	B3. Culvert barrel is less than 1.5 m in width and/or less than 1 m in height	8	No		
	B4. Culvert barrel is less than 1 metre square in cross-sectional area	10	Yes	10	
	B5. Additional evidence (potential score between 1 and 10)		No		User can input additional evidence categories and their suggested potential score
	Maximum score for Factor B:	10		Column maximum B	10
C - Hydraulic performance of culvert					
The flow regime at the culvert inlet and through the barrel can be a factor on how floating debris and bed sediment is or isn't transported through the culvert	C1. Culvert never flows full for any part of its length	1	Yes	1	
	C2. Culvert flows full for all or part of its length during a flood in excess of 1 in 10 (10% chance)	2	No		
	C3. Culvert flow regime not known or not calculated yet	5	No		
	C4. Culvert flows full for all or part of its length during less than a 1 in 10 (10% chance) flood	8	No		
	C5. Culvert flows full for part of its length during normal flow	8	No		
	C6. Culvert always flows full (eg inverted siphon)	10	No		
	C7. Additional evidence (potential score between 1 and 10)		No		User can input additional evidence categories and their suggested potential score
	Maximum score for Factor C:	10		Column maximum C	1
D - Potential for large debris entering the watercourse and being transported downstream					
Larger debris which can be transported along the watercourse such as tree branches, 'mats' of vegetation. pallets and silage bales pose the	D1a. No past blockage or evidence of large debris within the watercourse or on its banks	1	Yes	1	
	D1b. Evidence of large loose debris collecting within the watercourse or its banks	10	No		
	D1c. Evidence of large floating mats of vegetation/regular cutting of vegetation within the channel	10	No		
	D2. Steep gradient on approach watercourse (greater than 1 in 100)	10	No		

Name of culvert or outfall:	New access road
Location of culvert or outfall:	Newsells winery
Person completing this initial assessment:	Mark Davison
Date of assessment:	04 March 2024

1 Initial debris screen need score (IDSNS)

Main factor (blockage risk source)	Evidence/sub-factor (choose all that are applicable)	Potential score	Applicable?	Score	Comments
greatest risk of blockage of a culvert barrel. The source of these can be deliberate dumping into the channel or from being washed into the river from nearby properties.	D3a. Past incident(s) of partial blockage of culvert or channel by debris (less than 30% of the cross-sectional area)	15	No		
	D3b. No Information on past or potential debris load/do not know	15	No		
	D3c. Past incident(s) of significant blockage of culvert or channel by debris (30% to 50% of the cross-sectional area)	20	No		
	D3d. Past incident(s) of blockage of culvert or channel by debris (more than 50% of the cross-sectional area)	30	No		
	D4. Additional evidence (potential score between 1 and 30)		No		
	Maximum score for Factor D:	30		Column maximum D	1
E - Potential for debris to collect within the culvert barrel					
The presence of one or more physical attributes of the culvert barrel which can trap floating debris or bed sediment will influence the chance of a blockage.	E1a. Culvert barrel has a constant bed slope which is steeper than 1 in 200	1	No		
	E1b. Culvert barrel has a constant bed slope which is less than 1 in 200	3	Yes	3	
	E1c. Culvert barrel has a gradual change (slackening) in bed slope	5	No		
	E1d. Culvert barrel has a sudden change (slackening) in bed slope	10	No		
	E2a. Culvert barrel is straight (no bends, obstructions or change in cross-section area)	1	Yes	1	
	E2b. Culvert barrel has minor bends (less than 20 degrees)	2	No		
	E2c. Culvert barrel has significant bends (more than 20 degrees)	5	No		
	E3a. Culvert barrel cross-section area changes by less than ±25 % and the transition is tapered	2	No		
	E3b. Culvert barrel cross-section area changes by less than ±25 % and the transition is sudden	4	No		
	E3c. Culvert barrel has mammal shelves (other than concrete benching in the invert)	5	No		
	E3d. Culvert barrel cross-section changes by more than ±25 % and the change is tapered	10	No		
	E3e. Culvert barrel cross-section changes by more than ±25 % and the change is sudden	25	No		
	E4a. Low weir within culvert (less than 0.5 m vertical drop)	5	No		
	E4b. High weir within culvert (more than 0.5 m vertical drop)	15	No		
	E5a. Service crossings in lower half of culvert height	30	No		
	E5b. Service crossings in upper half of culvert height	35	No		
	E6a. Vertical dividing walls within the barrel (less than half culvert height)	35	No		
	E6b. Vertical dividing walls within the barrel (more than half culvert height) or culvert splits into multiple barrels along its length	40	No		
	E7. Culvert has a sluice gate that is normally partly closed, a non-return valve on the outlet, or a 'letterbox' outlet	25	No		
	E8. Culvert has an outlet security screen	25	No		
	E9. Culvert is an inverted siphon or 'sag culvert'	25	No		
	E10. Consequences of a culvert blockage are significant (eg immediate receptors for flow not able to pass through the culvert are	30	No		

Name of culvert or outfall:	New access road
Location of culvert or outfall:	Newsells winery
Person completing this initial assessment:	Mark Davison
Date of assessment:	04 March 2024

1 Initial debris screen need score (IDSNS)

Main factor (blockage risk source)	Evidence/sub-factor (choose all that are applicable)	Potential score	Applicable?	Score	Comments
	E11. Past evidence of substantial blockage (>50%) of culvert cross-sectional area	40	No		Check should be made on whether an outlet screen is still needed
	E12. Culvert is part of the inlet to a pumping station	45	No		
	E12. Additional evidence (potential score between 1 and 45)		No		User can input additional evidence categories and their suggested potential score
	Maximum score for Factor E:	45		Column maximum E	3
F - Presence of other features that could trap debris elsewhere/other mitigation (note these are zero or minus scores)					
	F1. There is another smaller capacity culvert, weir or bridge up to 100 m upstream of the culvert inlet	-5	Yes	-5	The upstream road acts as a weir
	F2. Flow through the culvert barrel in flood will be rapid (velocity greater than 1 m/s and no intermediate piers or service crossings)	-15	No		High flow velocities during flood flows will keep smaller debris mobilised, especially if no internal obstructions.
	F3. Adequate management measures in place to reduce the chance of large debris getting into the channel	-20	No		
	F4. Consequences of a culvert blockage are small (eg an alternative flow route exists which would not lead to an increase in flood damage or an increased safety hazard)	-25	No		
	F5a. Coarse screen exists or is to be constructed upstream within 100 metres of the culvert inlet	-10	No		
	F5b. Coarse screen exists or is to be constructed upstream of the culvert and there is no likely source of additional debris between the	-25	No		
	F6. Additional evidence (potential score between 0 and minus 25)		No		User can input additional evidence categories and their suggested potential score
	Minimum score for Factor F:	-25		Column minimum F	-5
				TOTAL of Factors A-F	11
				If the total of factors A-F is negative, then the total is set to zero	
Decision rule:				A debris screen is not required	

B Hand calculations

Hand calculations were carried out for rectangular and circular culverts following the CIRIA culvert guide.

B.1 Rectangular culverts

The calculations assume standard size box culverts of 1.0 m wide and 0.5 m high internal dimensions. The Manning n in the culvert was set to 0.012 for a new culvert. The upstream invert level of the culverts has been assumed to be 65.4 m AOD, which is the average ground level on the over land flow route upstream of the proposed access road. The downstream invert level has been assumed to be 65.3 m AOD which is the average ground level downstream of the proposed access road. The culvert barrel length was set to 5.4 m based on measurements of the width of the proposed access road shown on the Clients site drawings. The slope is 0.0185 m/m based on values taken from the LiDAR upstream and downstream of the proposed access road.

Inlet control

Assuming a design flow of 0.2 m³/s for each culvert based on a set of 4 culverts the ratio of $1.811 Q / AD^{0.5}$ of 1.02 is less than the threshold of 3.5 which means that the culvert is unsubmerged.

The critical depth in the culvert (y_c) was estimated using an iterative solution of the equation: $Q^2 T / g A^3 = 1$. This was 0.16 m.

The critical velocity in the culvert barrel was then estimated using $Q / (T y_c)$. This was estimated to be 1.25 m/s.

The water depth upstream of the culvert was estimated as 0.266 using equation: $H_w / D = H_c / D + K (1.811 Q / AD^{0.5})^M - 0.5s$.

The inlet headloss was estimated as 0.009 m using equation: $h_i = K_i (V_b / 2g)$ and $V_b = Q / Ab$.

The total water depth above the invert level of the culvert is therefore $0.266 + 0.006 = 0.272$ m, which is an upstream water level of 56.67 m AOD. This is slightly lower than the 0.30 m estimated from the hydraulic model with 4 rectangular culverts of 1.0 m by 0.5 m.

Outlet control

The water level upstream of the culvert is checked for outlet control where the water level upstream is the sum of inlet, barrel and outlet losses plus the downstream water level.

The water level downstream of the culvert taken from the 2D hydraulic model is 65.40 m AOD.

The outlet headloss was estimated as 0.004 using equation: $h_o = K ((V_b^2 / 2g) - (V_{dc}^2 / 2g))$, where V_{dc} the downstream velocity of 0.3 was taken from the 2D hydraulic model.

The headloss due to friction was estimated as 0.015 m using equation: $h_f = n^2 L V^2 / R^{4/3}$.

The upstream water level is therefore $65.40 + 0.009 + 0.004 + 0.015 = 65.424$ m AOD. This is lower than calculated for inlet control and confirms that flow through the culverts is inlet controlled.

B.2 Circular culverts

The calculations assume standard size circular culverts of 0.3 m diameter internal dimensions. The Manning n in the culvert was set to 0.012 for a new culvert.

Inlet control

Assuming a design flow of 0.05 m³/s for each culvert based on a set of 15 culverts the ratio of $1.811 Q / AD^{0.5}$ of 2.3 which is less than the threshold of 3.5 which means that the culvert is unsubmerged.

The critical depth in the culvert (y_c) was estimated using an iterative solution of the equation: $Q^2 T / g A^3 = 1$. This was 0.141 m.

The critical velocity in the culvert barrel was then estimated using $Q / (T y_c)$. This was estimated to be 1.18 m/s.

The water depth upstream of the culvert was estimated as 0.226 using equation:

$$H_w / D = H_c / D + K (1.811 Q / AD^{0.5})^M - 0.5s.$$

The inlet headloss was estimated as 0.013 m using equation: $h_i = K_i (V_b / 2g)$ and $V_b = Q / A_b$.

The total water depth above the invert level of the culvert is therefore $0.266 + 0.013 = 0.279$ m, which is an upstream water level of 56.68 m AOD. This is slightly higher than the 0.26 m estimated from the hydraulic model with 15 circular 0.3 m diameter culverts.

Outlet control

The water level upstream of the culvert is checked for outlet control where the water level upstream is the sum of inlet, barrel and outlet losses plus the downstream water level.

The water level downstream of the culvert taken from the 2D hydraulic model is 65.40 m AOD.

The outlet headloss was estimated as 0.021 using equation: $h_o = K ((V_b^2 / 2g) - (V_{dc}^2 / 2g))$, where V_{dc} the downstream velocity of 0.3 was taken from the 2D hydraulic model.

The headloss due to friction was estimated as 0.038 m using equation: $h_f = n^2 L V^2 / R^{4/3}$.

The upstream water level is therefore $65.40 + 0.013 + 0.021 + 0.038 = 65.472$ m AOD. This is lower than calculated for inlet control and confirms that flow through the culverts is inlet controlled.

We design smarter, more resilient solutions across both the natural and built environment to help everyone live and work more sustainably with water.

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