A9.1: Surface Water Hydrology

1 Introduction

1.1.1 This appendix provides additional information on the methodology and calculations used to inform the surface water (both high flow and low flow) hydrology of the proposed scheme, as reported in Chapter 9 (Road Drainage and the Water Environment) of the DMRB Stage 3 ES. The methodologies and supporting calculations are presented in this appendix, whilst the assessment of the magnitude and significance of impacts and any subsequent requirements for mitigation are presented in Chapter 9.

1.1.2 Watercourses and hydrological features to be considered (from Luncarty to Pass of Birnam) that could potentially be impacted by the proposed scheme are:

- River Tay;
- Shochie Burn and its tributaries;
- Ordie Burn and its tributaries;
- Ardonachie Burn;
- Benchil Burn;
- Corral Burn;
- Garry Burn;
- Gelly Burn and its un-named tributaries;
- Broomhill Burn; and
- Birnam Burn.

1.1.3 Drainage considerations for the proposed scheme require the estimation of extreme flood flows at each of the watercourse crossing locations for the following annual exceedence probabilities (AEPs/return periods):

- 50%, 10%, 4%, 3.33%, 2%, 1%, 0.5% and 0.2% AEPs, which are equivalent to the 2, 10, 25, 30, 50, 100, 200 and 500-year return periods respectively.

1.1.4 Hydrological assessment requires the estimation of low flows at outfall locations, namely, Qmean (mean flow), q50 (50 percentile flow) and q95 (95 percentile flow).

1.1.5 Section 2 of this appendix describes the methodologies adopted for the estimation of the design low flow and high flow values. Section 3 presents a summary of design high flows estimated for each crossing. Section 4 provides a summary of the design low flow estimates at the outfalls and Section 5 contains a summary of the hydrological parameters estimated or extracted from the Flood Estimation Handbook (FEH) CD-ROM v.3 (CEH, 2009) for each watercourse.

1.1.6 The location of all the crossings and their corresponding catchment areas, together with the location of the six outfalls, are shown on Figure 9.2 of the ES.

2 Methodology

2.1.1 The following abbreviations/definitions are used in this appendix:

- AREA - Catchment Drainage Area (km^2);
- AEP - Annual Exceedence Probability;
- SAAR 1961-90 - Standard Average Annual Rainfall (mm);

- BFIHOST - Base Flow Index derived using the HOST classification;
- SPRHOST - Standard Percentage Runoff (%) derived using the HOST classification;
- FARL – an indices of Flood Attenuation due to Reservoirs and Lakes;
- FEH – Flood Estimation Handbook (CEH, 2009);
- FPEXT - the fraction of the catchment area estimated to be inundated by a 100-year flood;
- URBEXT2013 - FEH index of fractional urban extent for 2000, updated to 2013 using the FEH national model of urban growth;
- q95 - Flow that is expected to be exceeded 95% of the time (m^3/s);
- q50 - Flow that is expected to be exceeded 50% of the time (m^3/s);
- QMED - Median annual maximum flood flow (m^3/s) (the same as the flow with a two-year return period); and
- Q -Tyr (e.g. Q-5yr) - Flood flow associated with a T-year return period (e.g. five-year return period flow).

2.1.2 Hydrological pressures and flood risk impacts arising from the proposed scheme were assessed using the catchment parameters and methodologies shown in Table 1.

Table 1: Hydrological Parameters and Methodologies

Description/ Paramater	Methodology
Catchment area Parameter: AREA	The catchment areas for the larger catchments (>2km2) were obtained from the FEH Catchment Descriptors CROM. However many of the watercourses drain areas much smaller than this. The delineation of these catchment boundaries was based upon interpretation of 1m level contours derived from LIDAR imagery. Further cross checks were made using: watercourse observation from arial imagery; photographic evidence of flow and channel sizes matched to catchment areas; and watercourse mapping given on the SEPA 1:10,000 scale RBMP interactive map (SEPA, 2011) (http://gis.sepa.org.uk/rbmp/)
Median annual maximum flood Parameter: QMED	Estimation of the median annual maximum flood flow (QMED) was required in order to determine flood design peak flows and has been estimated for each of the watercourse crossings (except the Ordie Burn crossing) using the latest FEH QMED equation and following guidance as given by the Environment Agency (2012) regarding the use of donor catchments to refine estimates.(For the Ordie Burn SEPA operate a flow gauge immediately downstream of the crossing and the QMED for this site has been obtained directly from the gauged data). The FEH catchment descriptors methodology is found to perform better than other accepted methods for small catchments including the IH 124 methodology (Faulkner et al., 2012). Due to limitations within the FEH software at defining the boundary of catchments less than 0.5 km^2; where drainage areas are less than 0.5 km^2, FEH estimates have been calculated for a representative larger catchment area and appropriately scaled by the ratio of catchment areas. FEH guidance on the degree of uncertainty associated with QMED estimates from catchment descriptors alone is ± 55%.No quantified value of uncertainty exists for when refinements are made using donor catchments but the uncertainty will be less than ± 55%. This estimation of QMED provides a baseline characteristic for each watercourse and allows for potential impacts resulting from the proposed development to be assessed should there be an increase or decrease in drainage area, or some other change that could affect the runoff.
Flood Design Peak Flows Parameter: Q-Tyr	Standard application of the FEH statistical pooling group method was used to determine flood growth curves (up to the 500-year event) for a subset of target catchments that covered the range of catchment conditions experienced in the area of interest. Derived growth curves were then applied to the remaining target catchments according to their hydrological similarities. High flows were provided to support fluvial geomorphological assessments and the 0.5% AEP (200-year return period) design flow further used to guide culvert design and provide mitigation values to correctly size any structures across watercourses. This methodology provides baseline conditions as well as providing the necessary understanding of the flood flows when considering the impacts of either culverting or re-aligning a watercourse along the proposed scheme. No formal quantification of Q-Tyr uncertainty is provided in the FEH but it is likely to be at least in the order of the QMED uncertainty and in some circumstance will be appreciably larger.

Description/ Paramater	Methodology
50-percentile & 95-percentile flow Parameters: q50 q95	The q50 (50-percentile flow) and q95 (95-percentile flow) are baseline conditions and were provided to support water quality, ecological and geomorphological assessments. Where an adequate flow gauge exits the values are based directly on the gauge record. The q50 and q95 for ungauged watercourses were estimated by calculating the mean flow (Qmean) based on catchment area, SAAR and potential evaporation data at each of the subject sites; and scaling to q50 and q95 using the ratio of Qmean to q95, and Qmean to q50, obtained from local representative donor gauged catchments.

2.1.1 Annual maximum flow data are available for two hydrometric gauging stations on two rivers in the study area; Station 15027 - Garry Burn at Loakmill, and Station 15028 - Ordie Burn by Luncarty. Neither station is listed in the HiFlow-UK database. Consequently, SEPA was consulted regarding the high flow quality of the two records and in particular whether the data will provide useful QMED estimates. SEPA's response was that both stations could potentially be used for this purpose though station 15028 has less reliable quality and the recorded flows above QMED should be treated with particular caution. SEPA provided up to date AMAX series for both stations.

2.1.2 Apart from the catchment areas the FEH catchment descriptors for the two catchments are similar, suggesting the responsive nature of the rivers will be similar. However, the the ratio of QMED from the AMAX and QMED from FEH catchment descriptors was 2.37 at Station 15028 (Ordie Burn) whereas this ratio was only 1.33 at Station 15027 (Garry Burn). Based on this observation, coupled with SEPA's cautionary comments about the quality of the high flow rating at 15028, a review of the high flow records of the Ordie at Station 15028 at Luncarty was undertaken. The findings of this are presented in Annex A of this report. The review study concludes that equal weight is given to the two $QMED_{gauge}/QMED_{catchment\ descriptors}$ ratios of the Ordie and Garry Burn stations, giving an average adjustment factor of 1.75. This gives a QMED at the A9 crossing of 20.3m^3/s and this is the value taken forward in the project as the index flood to which the pooling group growth curve has been applied.

3 Summary of high flow estimates

3.1.1 The design flows presented in Table 2 are appropriate for the current period. In accordance with recent DEFRA research, SEPA recommends that an uplift of +20% be made to make an allowance for the likely effects of climate change by the 2050s time horizon.

Table 2: Design flood peak flows without an allowance for climate change (m^3/s)

[To make an allowance for climate change these values need to be increased by 20%]

Crossing	2yr	5yr	10yr	25yr	30yr	50yr	100yr	200yr	500yr
Shochie Burn (Crossing 1)	18.7	24.8	28.9	34.6	35.8	39.2	44.3	49.8	57.9
Ordie Burn (Crossing 2 @ Station 15028)	20.3	29.0	35.5	45.1	47.3	53.6	63.1	74.5	92.2
Gelly Burn (South)	2.3	3.3	4.0	5.1	5.4	6.1	7.2	8.5	10.5
Unnamed Tributary of Ordie Burn (Crossing 2a)	0.60	0.86	1.05	1.33	1.40	1.59	1.87	2.20	2.73
Unnamed Tributary of Ordie Burn (Crossing 2b)	0.45	0.65	0.79	1.00	1.05	1.19	1.41	1.66	2.05
Unnamed Tributary of Ordie Burn (Crossing 2c)	0.64	0.92	1.12	1.42	1.49	1.69	1.99	2.35	2.91
Unnamed Tributary of Ordie Burn (Crossing 2d)	0.23	0.33	0.40	0.50	0.53	0.60	0.71	0.83	1.03
Ordie Burn @ Newmill approach road (Crossing 2e)	17.0	24.3	29.8	37.8	39.7	44.9	52.9	62.5	77.3
Ardonachie Burn (Crossing 3)	0.59	0.81	0.98	1.24	1.30	1.47	1.75	2.09	2.63
Unnamed Drain 3 (Crossing 4)	0.025	0.035	0.042	0.053	0.056	0.063	0.075	0.09	0.113
Unnamed drain 4 (Crossing 5)	0.004	0.006	0.007	0.009	0.009	0.010	0.012	0.014	0.018
UnnamedTributary 1 of Gelly	0.031	0.043	0.052	0.066	0.069	0.079	0.094	0.111	0.140

Crossing	2yr	5yr	10yr	25yr	30yr	50yr	100yr	200yr	500yr
Burn (Crossing 5a)									
Unnamed Tributary 2 of Gelly Burn (Crossing 6)	0.051	0.070	0.085	0.108	0.113	0.128	0.153	0.182	0.229
Gelly Burn (North) (Crossing 7)	0.062	0.086	0.104	0.131	0.137	0.156	0.186	0.221	0.278
Unnamed Drain 5 (Crossing 8)	0.014	0.020	0.024	0.030	0.032	0.036	0.043	0.051	0.064
Unnamed Tributary 3 of Gelly Burn (North) (Crossing 9)	0.032	0.044	0.053	0.067	0.070	0.080	0.095	0.113	0.142
Broomhill Burn (Crossing 10)	0.088	0.121	0.146	0.185	0.194	0.220	0.262	0.312	0.392
Crossing Eleven	0.016	0.022	0.027	0.034	0.035	0.040	0.048	0.057	0.071
Crossing Twelve	0.026	0.036	0.043	0.055	0.057	0.065	0.077	0.092	0.116
Crossing Thirteen	0.075	0.103	0.125	0.158	0.165	0.188	0.223	0.266	0.334
Garry Burn (@ Station 15027)	7.9	10.9	13.2	16.7	17.5	19.8	23.6	28.1	35.4

4 Summary of low flows

4.1.1 The estimated low flow values are presented in Table 3.

Table 3: Estimated low flows at outfall locations

River	Unit	q95	q50	Mean flow
River Tay @ Luncarty	m³/s	45	136	175
Shochie Burn	m³/s	0.061	0.443	0.796
Ordie Burn	m³/s	0.088	0.642	1.154
Ordie Burn No. 2	m³/s	0.071	0.520	0.934
Garry Burn	m³/s	0.031	0.207	0.375
Gelly Burn	l/s	0.1	0.68	1.2

5 Summary of baseline hydrological catchment parameters

5.1 Introduction

5.1.1 This section presents the catchment descriptors and hydrological parameters for each of the watercourses and outfalls. Table 4 presents FEH catchment descriptors, extracted from the FEH CD-ROM v.3 (CEH, 2009) and amended where necessary, based on local information of the OS map.

Table 4: FEH catchment descriptors for each of the watercourses and outfall locations

Watercourse and Crossing Number	Grid Reference	Area km²	SAAR (mm)	BFIHOST	SPRHOST (%)	FARL	URBEXT (2013)
Shochie Burn (Crossing 1)	NO09450 30350	38.3	1041	0.52	41	0.969	0
Ordie Burn (Crossing 2 @ Station 15028)	NO08900 31150	57.3	934	0.59	37	0.991	0.005
Unnamed Tributary of Ordie Burn (Crossing 2a)	NO08150 32500	1.67	789	0.54	41	1	0
Unnamed Tributary of Ordie Burn (Crossing 2b)	NO08800 31650	1.26	780	0.69	32	1	0
Unnamed Tributary of Ordie Burn (Crossing 2c)	NO08150 32500	1.80	789	0.54	41	1	0
Unnamed Tributary of Ordie Burn (Crossing 2d)		0.60	780	0.69	32	1	0
Ordie Burn @ Newmill approach road (Crossing 2e)	NO08150 32250	46.6	934	0.59	37	0.991	0.005
Gelly Burn (South)	NO08500 31700	6.66	855	0.57	43	1	0

Watercourse and Crossing Number	Grid Reference	Area km²	SAAR (mm)	BFIHOST	SPRHOST (%)	FARL	URBEXT (2013)
Garry Burn @ Station 15027	NO07449 34013	18.3	947	0.57	37	0.999	0.0119
Ardonachie Burn (Crossing 3)	NO07150 34850	1.7	854	0.58	43	1	0
Unnamed Drain 3 (Crossing 4)	NO07650 35950	0.07	871	0.62	40	1	0
Unnamed Drain 4 (Crossing 5)	NO07650 35850	0.011	871	0.62	40	1	0
Unnamed Tributary 1 of Gelly Burn (Crossing 5a)	NO07650 35850	0.082	871	0.62	40	1	0
Unnamed Tributary 2 of Gelly Burn (Crossing 6)	NO07200 37350	0.128	890	0.63	35	1	0
Gelly Burn North (Crossing 7)	NO07200 37350	0.156	890	0.63	35	1	0
Unnamed Drain 5 (Crossing 8)	NO07200 37350	0.036	890	0.63	35	1	0
Unnamed Tributary 3 of Gelly Burn (North) (Crossing 9)	NO07200 37350	0.080	890	0.63	35	1	0
Broomhill Burn (Crossing 10)	NO07250 38100	0.207	899	0.62	31	1	0
Crossing Eleven	NO07250 38100	0.039	899	0.62	31	1	0
Crossing Twelve	NO07250 38100	0.061	899	0.62	31	1	0
Crossing Thirteen	NO07250 38100	0.177	899	0.62	31	1	0

6 References

CEH (2008). Improving the FEH statistical procedures for flood frequency estimation. Science Report: SC050050. Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme.

CEH (2009). Flood Estimate Handbook (FEH) CD ROM v3. Centre for Ecology and Hydrology.

Environment Agency (2012). Flood estimation guidelines: Operational instruction 197_08, Version 4 (Issued 26/06/2012).

Faulkner, D., Kjeldsen, T., Packman, J., and Stewart, L. (2012). Estimating flood peaks and hydrographs for small catchments: Phase 1; Project: SC090031. Environment Agency.

SEPA (2011) River Basin Management Plan (RBMP) Interactive Map [online]. http://gis.sepa.org.uk/rbmp/

SEPA (undated). Technical Flood Risk Guidance for Stakeholders (Version 3).

Syme, W.J. (2001). Modelling of bends and hydraulic structures in a two dimensional scheme. Institute of Engineers, Australian Conference on Hydraulics in Civil Engineering, Hobart 28-30 Nov 2001.

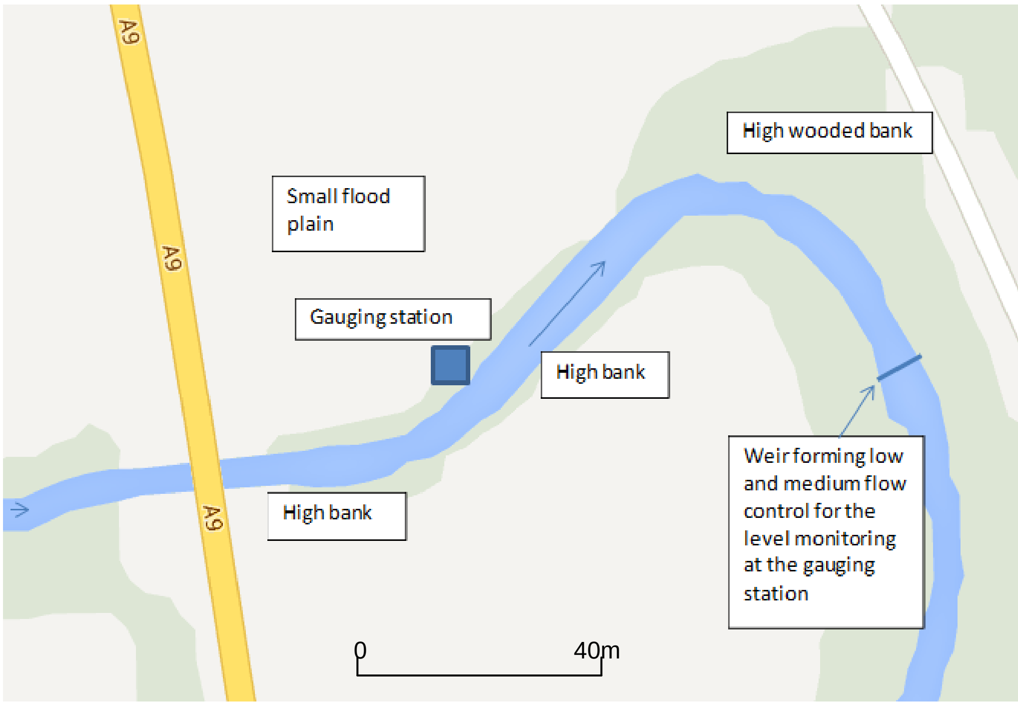
Annex A: Review of the Ordie Burn at Luncarty high flow record

Background

The estimation of design flood flows should seek to include appropriate local gauged data when ever this is available. This is strongly advocated in the Flood Estimation Handbook suite of methods for design flow estimation. In the case of the A9 crossings of the Ordie Burn there is seemingly a particularly well located SEPA flow gauge (Station no 15028: Ordie Burn @Luncarty) immediately downstream of the present A9 crossing of the watercourse. If the high flow record were to be of sufficiently good quality then this has the potential to significantly improve the quality of the design flow estimations available to the project. However the gauge was not installed to monitor flood flows, rather its purpose was to monitor the low and medium flows. Consequently the calibration of the gauge has focused on these lower flows and the gauge does not appear in the Hiflows-UK dataset (the national database of flood flow data used by the FEH analysis package). But given its close proximity to the targeted reaches of interest, SEPA was consulted concerning its potential use in estimating the median annual flood (QMED) which is used as the index flood in the FEH procedures and is critical to the accuracy of the resulting design flows.

Figure 1A provides the indicative location of the gauge in relation to the A9, its hydraulic control (a weir), and the shape of the river.

Figure 1A: Location of the Ordie Burn at Luncarty gauging station



The Issue

SEPA Hydrometry suggested that although the gauge is not perfect its record may offer a useful estimate of the QMED flow. Simple acceptance of the full period of record gave an estimate of QMED that:

i. Resulted in a QMEDgauge/QMEDCatchment descriptors ratio of 2.38. This value is unusually high (2.8 standard deviations from the mean of all Scottish gauges found in the Hiflows-UK database).

ii. The QMEDgauge/QMEDCatchment descriptors ratio is much larger than equivalent values for surrounding gauges in the region (Table 1A).

Table 1A – Regional $QMED_{gauge}/QMED_{Catchment\ descriptors}$ ratio

Station number	QMED Ratio
14001	1.27
15008	1.35
15010	1.12
15013	1.36
15027	1.33
15028	2.37
16004	1.20

iii. The $QMED_{gauge}/QMED_{Catchment\ descriptors}$ ratio of 2.37 markedly differs to that of the Garry Burn at Loakmill (1.33). The Garry Burn gauge is upstream of the Ordie Burn gauge and samples 37% of the Ordie Burn gauge's catchment area.

iv. Based upon experience the resulting 200-year flow of $101m^3/s$ looks unusually large for the size of the watercourse.

Given this it was considered justifiable to review the suitability of the high flow rating.

SEPA's comments on gauge performance

Obtaining the views and opinions of the hydrologists operating the gauging station is seen as a very useful source of information that will enhance the understanding. SEPA was very helpful in replying to our queries and requests for data. They provided the following summary regarding the uncertainties associated with the high flow rating.

> *"High flow gaugings (within bank flow) were originally obtained from a cableway downstream of weir control. The cableway was put out of action in 1990 and minimal high flow gaugings have been carried out at this location. Luncarty gauging station was installed as a low to moderate flow station for water resources/irrigation.*
>
> *The fisheries board cut a notch in the weir in February 2006. A gauging carried out during March 2006 indicated that there was increased flow since the notch was introduced to the weir. There have only been two further moderate flow gaugings carried out in 2007 and 2009.*
>
> *Access was restricted to the site so no gaugings were carried out between late 2009 and 2012. A high flow rating was produced for indicative information but inadequate gauging above 0.5m (wading limit) have been carried out to confirm the expected increase in flow since the notch was introduced to the weir. The high flow rating should be treated with caution for data after 2005.*
>
> *Channel changes and bank erosion may have occurred during high flows of 2009 but more notable changes have been evident since the high flows of January 2011 when the lease for the site was being negotiated.*
>
> *Issues with trees on the weir have been noted on several occasions in recent years.*
>
> *There is no recent moderate flow cross-sections or out of bank cross-sections available for this location at present. At present the zero of the gauge is unknown".*

In further correspondence SEPA indicated that they had greater confidence in the Garry Burn at Loakmill high-flow rating since a detailed review had been undertaken for it in 2010 for a flood study in Bankfoot.

A further useful insight was that SEPA used to operate another gauging station on the Ordie Burn at Jackstone (Stn No 015032), NGR NO 070 337. This gauged a similar sized catchment as that of the adjacent Garry Burn and the pair had been used by SEPA in an earlier study to compare the two flow regimes. This found that the characteristics of the Jackstone hydrograph were different from that of the neighbouring Garry Burn at Loakmill. The Ordie Burn had a flashier response to rainfall storms, rising fast to a high peak flow before receding sharply. Considering this SEPA would accept that a real runoff rate for the Ordie Burn at Luncarty gauging station could be slightly higher than that for Loakmill. It is understood that the Jackstone gauge was not calibrated to be a high flow gauge so actual quantification of peak flood flows would not have been available. This data was not available to the current project.

The following section describes the review that Jacobs undertook to assess the appropriateness of using the Ordie Burn at Luncarty for the estimation of QMED, or whether there are good grounds for not using the data.

Review

Spot gaugings and existing high flow rating

Figure 2A graphically presents all the spot gaugings together with the SEPA high-flow rating. The numerical details of this rating are given in the box below.

QHigh/POT.M1 (relative to gauge datum)

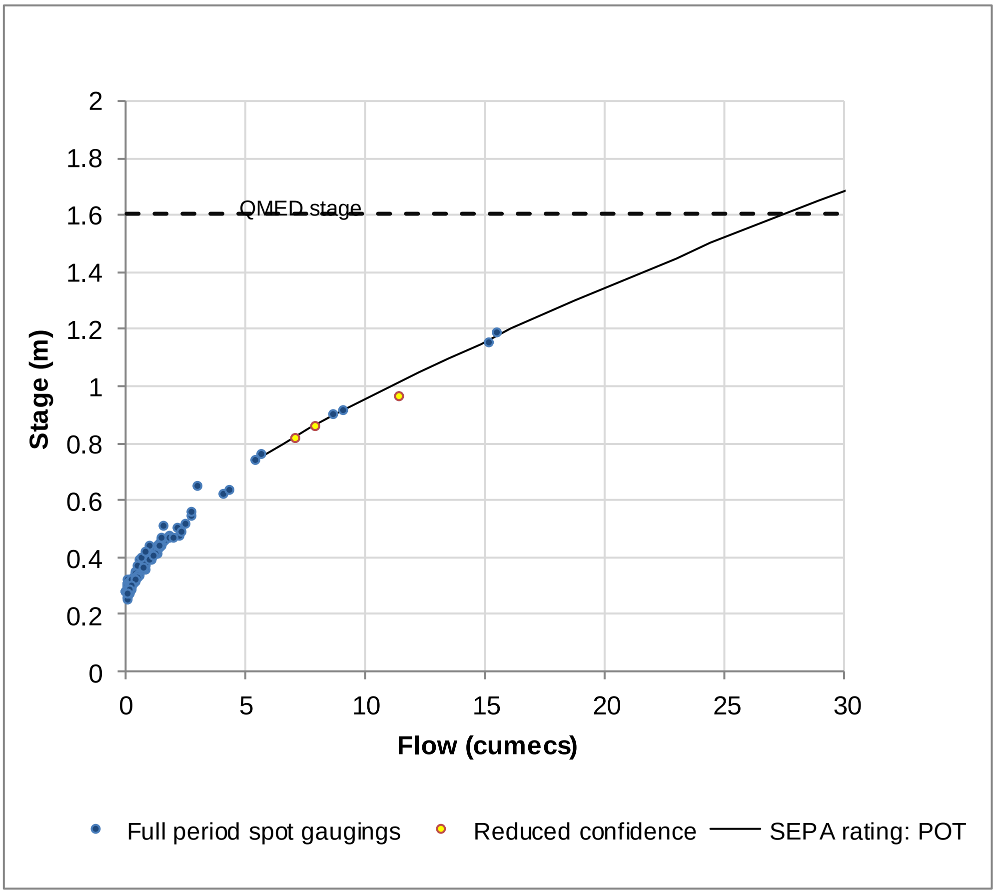
Rating curve	POT
Comment	
Version	M1
Last change	10 December 2009
Comment	created from gaugings excl. march 2007

Validities for QHigh/POT.M1

From Transition since	Valid since	Valid to	Transition to After
	01/01/1990 09:00:00		

0.740 m < SG < 1.189 m QHigh(SG) = 20.7638 * (SG - 0.372337)^1.35267 [m³/s]

Figure 2A: Spot gaugings and rating for the Ordie Burn @ Luncarty gauge



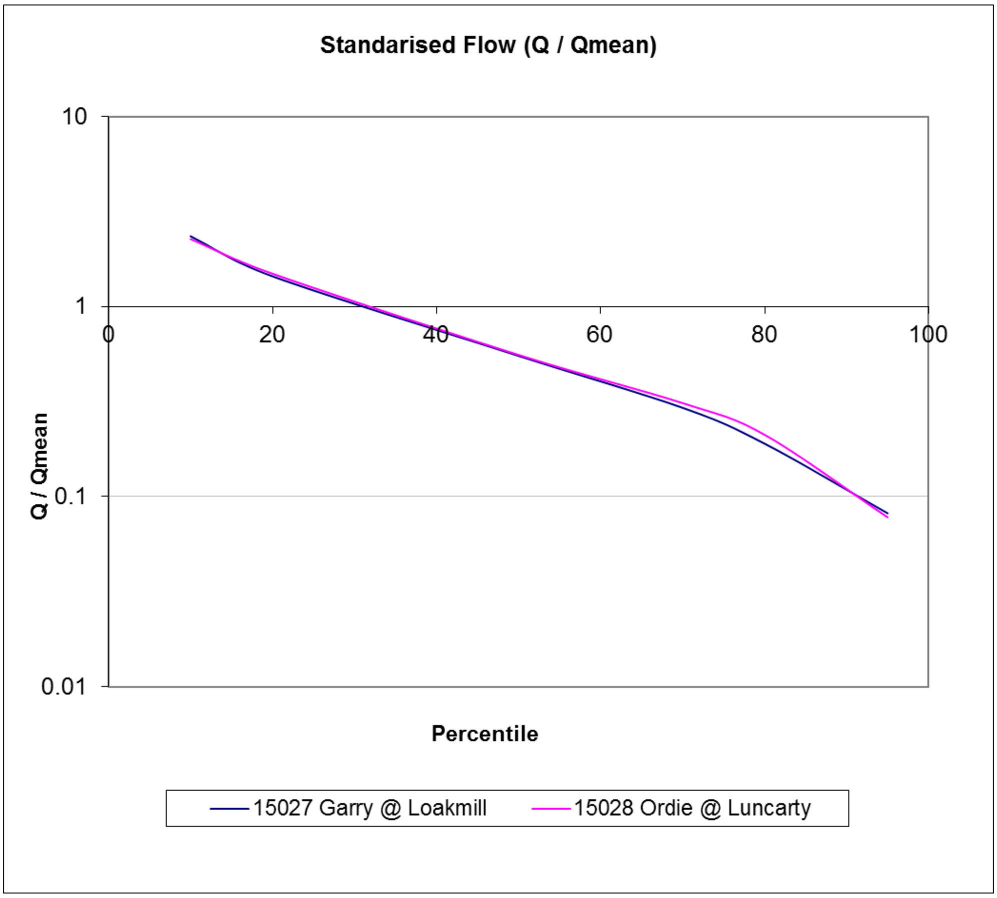
Included in Figure 2A is the stage for the 2-year return period as determined from the full annual maximum series (i.e. the QMED stage). The yellow marked gaugings are those that SEPA has identified as having reduced confidence. The spot gaugings align reasonably well and only show limited variability. Both the spot gaugings of approximately 15m^3/s relate to the same event and were taken at the beginning of the station record. Obtaining recent confirmatory gaugings of these would be particularly helpful since at present the high flow rating is particularly reliant upon this early gauging.

Based on the visual alignment of the SEPA rating to the higher spot gaugings, the rating appears to be a sensible line of best fit. However, as discussed below, the acceptance of this extrapolation may not be valid over the range required to make an estimate of the QMED. As portrayed the extrapolation suggests that the spot gaugings only sample up to just over 0.5 QMED. This is on the low side and limits the confidence that can be assigned to the QMED estimate, though by itself does not preclude its use.

<u>Relative flashiness of the Garry and Ordie Burns</u>

To investigate the SEPA observation that distinct differences in flashiness exist between the Ordie Burn and the Garry Burn the flow duration curves of the Ordie Burn at Luncarty and the Garry Burn at Loakmill were compared (Figure 3A). The steepness of flow duration curves is generally taken to be a measure of the flashiness of a watercourse. The steeper the curve the more responsive and flashy the flow regime. Figure 3A suggests that based on this measure there is little difference between the two stations which implies some degree of hydrological similarity. No data for the now closed Ordie Burn at Jackstone were readily available to investigate this issue further. It is understood that neither the Ordie Burn at Jackstone nor the Ordie Burn at Luncarty are high flow stations. Consequently it may be speculated that distinct uncertainty could exist in the shape and magnitude of flood flow hydrographs. Such speculation cannot, however, be used to discount SEPA's observations of differences, for example the time taken to react to rainfall can be investigated without accurate ratings.

Figure 3A: Comparison of the standardized flow duration curves for Ordie Burn at Luncarty and Garry Burn at Loakmill



In conclusion, based on the information available, the issue raised by SEPA does warn of an appreciable difference in the responsiveness of the upper reaches of the Ordie Burn compared to the similarly sized Garry Burn. But downstream at the Ordie Burn at Luncarty station the difference to the Garry Burn in the general flashiness of the flow regimes is not particularly evident. This is interpreted as not giving strong grounds for expecting a significant difference in the $QMED_{gauge}/QMED_{Catchment\ descriptors}$ ratio, though further work would be required if this issue needed to be resolved.

Suitability of the site characteristics for rating extension for high flow estimation

Two issues have been identified that may prevent confident extrapolation of the existing rating curve to higher flows to permit a good QMED estimation. These issues are covered under a) and b) below.

a. *The sharp right-hand bend between the gauging station and the weir that forms the low and medium flow control.*

There is a risk that the sharp right-hand bend, which will cause a significant change in the velocity of the water, will increase the level of the water. The magnitude of this "form loss" is proportional to the square of the velocity. The magnitude of the effect can be estimated based on the following equation (taken from Syme, 2001):

Form losses result from rapid changes in velocity (magnitude or direction) such as when water is forced to contract, expand or flow round a bend. The head loss is typically expressed as a function of the dynamic head as given by Equation 2, where ζ is the form loss coefficient and g is the acceleration due to gravity ($9.81m^2/s$). Form losses are typically the dominant energy loss mechanism through hydraulic structures of short length and high velocities. Typically ζ varies from 0.5 to 1.5 of a dynamic head ($V^2/2g$).

$$\Delta h = \zeta \frac{V^2}{2g} \quad (2)$$

T

Table 2A gives Δh estimates for a range of velocities where ζ is assumed to have a value of 0.5. This non-linear effect will manifest itself to a larger degree as the velocity increases and it is speculated that the spot gaugings at lower flows (velocities) wont have been particularly influenced by this effect. To extrapolate without an allowance for this effect may result in an overestimation of the high flows. Without a detailed model of the somewhat complicated reach it is not possible to provide a firm estimate of the significance of this effect.

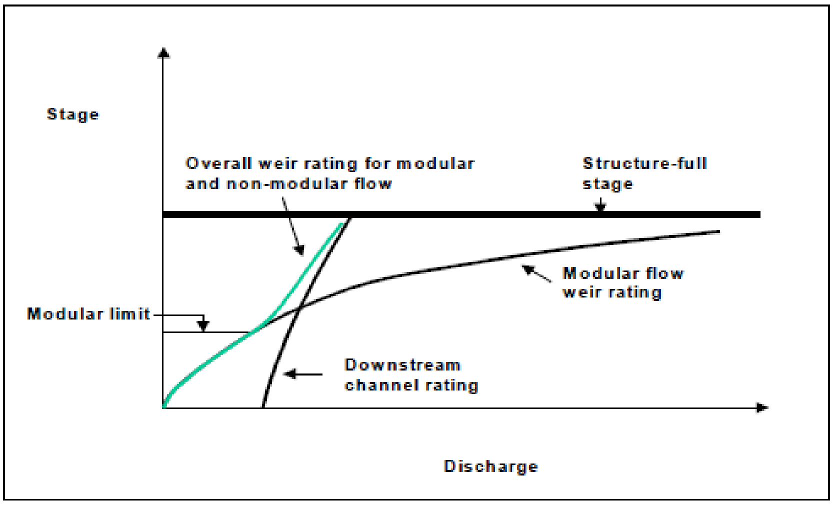
Table 2A: Estimated indicative change in water level due to the form losses associated with the right-hand bend between the stage monitoring location and the weir

Velocity of the water (m/s)	Δh (m)
1	+0.026
2	+0.102
3	+0.230

b. Drowning of the weir at high flows

The weir downstream of the right-hand bend is understood to form the hydraulic control for the station during low and medium flows. However, at higher flows weirs generally reach a flow where they drown and the control passes to the channel downstream. The general effect of this upon rating relationships is shown in Figure 4A. Without a detailed hydraulic model of the Ordie Burn reach, or preferably a range of higher high flow spot gaugings, it is not possible to quantify the potential significance of the effect to the Ordie Burn rating relationship. It is speculated that to extrapolate without an allowance for this effect might result in an overestimation of the high flows.

Fgure 4A: In-bank structure rating curve with drowning – constant downstream rating curve
[Source: Ramsbottom DM & Whitlow CD, 2003. Extension of rating curves at gauging stations best practice guidance manual. Environment Agency Manual – R&D Manual W6-061/M)



In addition to the above two issues SEPA has also observed the following issues that may also impair the quality of the estimated flows:

> *"The fisheries board cut a notch in the weir in February 2006. A gauging carried out during March 2006 indicated that there was increased flow since the notch was introduced to the weir. There have only been two further moderate flow gaugings carried out in 2007 and 2009.*
>
> *Access was restricted to the site so no gaugings were carried out between late 2009 and 2012. A high flow rating was produced for indicative information but inadequate gauging above 0.5m (wading limit) have been carried out to confirm the expected increase in flow since the notch was introduced to the weir. The high flow rating should be treated with caution for data after 2005.*
>
> *Channel changes and bank erosion may have occurred during high flows of 2009 but more notable changes have been evident since the high flows of January 2011 when the lease for the site was being negotiated.*
>
> *Issues with trees on the weir have been noted on several occasions in recent years".*

Another common source of rating relationship extrapolations leading to flawed estimates of high flow is when the channel cross-sections suddenly change shape. A common example is when flood waters spread and flow along a floodplain where the station is situated. There is potential for flood waters to pass by the Ordie gauge on the small flood plain. However, the high flow control is judged to be formed by a combination of the weir and the immediate downstream channel rather than the channel including the floodplain at the location of the station. For this reason the small flood plain behind the station is thought unlikely to significantly influence the high flow rating. However, this also adds an additional level of complexity to the hydraulics of the reach, as does the existence of the A9 culvert immediately upstream of the gauge.

<u>Conclusion regarding the use of the Ordie Burn data to refine QMED estimation</u>

The hydraulic complexity of the reach renders simple extrapolation of the rating equation to flows above the highest spot gaugings an uncertain procedure. In particular the possible effects of the weir drowning and the form losses associated with the tight bend are speculated as possible reasons for the current rating to overestimate flood flows. There are also other site-specific issues that have given cause for SEPA to recommend particular caution be placed on the post 2005 flows.

The FEH catchment descriptors estimate of QMED is 11.6m^3/s. This estimate is based on the revised FEH QMED equation given in CEH (2009).

The QMED calculated from the annual maximum series (excluding post 2005) based on the extrapolation of the current SEPA rating gives the QMED to be 25.4m^3/s.

The Garry Burn at Loakmill has a $QMED_{gauge}/QMED_{Catchment\ descriptors}$ ratio of 1.33. When this is applied as an adjustment factor to the Ordie at Luncarty catchment descriptor estimate of QMED this gives a QMED of 15.4m^3/s. This matches the highest spot gaugings (Figure 2A). However the QMED stage (excluding post 2005 data) of 1.53m indicates that the QMED must be higher than this highest spot gauging.

Therefore equal weight is given to the two $QMED_{gauge}/QMED_{Catchment\ descriptors}$ ratios of the Garry and Ordie Burn stations giving an average adjustment factor of 1.75. This gives a QMED at the A9 crossing of 20.3m^3/s and this is the value taken forward in the project as the index flood to which the pooling group growth curve has been applied. This factor is also used in the estimation of the Ordie Burn flow at the Newmills crossing.