Archimedean Screw

Hydropower scheme at

Guyzance Meander

Stage-Discharge Modelling

of local water levels and proposed proportional take scheme to derive the control equation for operation of the scheme

16th November 2018

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23.11.2018 revised issue, incorporating analysis of field data by Greg Nau of Mann Power

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23.11.2018

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23.11.2018

Executive summary

This document describes how water level data is gathered at site in 2018 and referenced to Qn values derived from the simultaneous flow data from the Morwick gauging station (#22001, on the Coquet), in order to illustrate the naturally-occurring water levels at the intake and discharge to the new scheme - this being the upper and lower limit of the depleted reach which is affected by the proposed changed flow regime. This thorough understanding of how levels currently vary at this site serves to qualify the assessed environmental impacts of the scheme.

The same data allows several equations to be formulated which will serve as the basis for the programmed control logic under which the hydropower scheme will operate. This method has been operating successfully for some years in other UK hydropower schemes that use a Proportional Take abstraction rule (e.g. Brahan Estate; Aberdeen Community Energy scheme at Donside). The analysis and operating regime in this analysis are based on minimum residual flow equivalent to Q75 with above this level a 50/50 split of flows (between hydropower system & residual). Because in practice there is also a minimum flow required to start the hydropower system, this regime actually means that the system does not start to abstract until the river attains approximately Q70.

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Data gathering

Water Level Data

Submerged pressure gauges were installed at the intake and discharge locations for the proposed development. These gauges were surveyed (Levels & Locations) so that they could be used to log water levels (mAOD) at 15-minute intervals. These sensors collected data from October 4, 2018 to November 7, 2018.

River Flow Data

Two sequences of data were gathered and used in this analysis. The first was a long-term sequence of daily average flows at the Morwick gauging station. This sequence spanned from October 1963 to October 2018 and was used to determine the flow duration curve for the river. The second data set was from the same gauge, but at 15-minute intervals from October 4 to October 21, 2018. This time record encompassed a suitably representative range of flows for the Coquet, including both low flows and a moderately high flow condition (roughly Q7).

Data analysis

Analysis Objectives

There are two principal objectives:

1. Develop equation for **water level** at the **discharge** Vs **river flow**
2. Develop equation for **water level** at the **intake** Vs **river flow**

Flow Data Preparation

Flow Adjustment

The hydropower system location is upstream of the Morwick gauging station. The distance from the proposed intake to the gauging station is approx 6270m. The catchment at the station is 569.8 km^2. We estimate the catchment where the system intake is located to be 550 km^2. Therefore, gauge station flow values are all adjusted by 550/569.8 = 96.53%.

Time Adjustment

There is a time delay between when a particular flow passes the hydropower site and when that flow reaches the downstream Morwick gauge. Because of this, the water level measurements at the site represent events which each need to be correlated with a flow recorded at the gauge at a later time.

The Morwick gauge is approximately 4670 m from the discharge point of the hydropower system and 6270 m from the intake point. The average distance is 5470 m. We assume the average river velocity (over most conditions) is 1 m/s, therefore the flow gauge data is 5470 seconds or 91 minutes behind the water level measurements at the site.

To represent this, we will offset the entire flow record (during the time the depth sensors were deployed) by 1.5 hours. For example, we would correlate the 12:30 water level data with flow data recorded at 14:00. We have benchmarked this assumption by close analysis of individual event peaks within the 15-minute datasets, and have found it to give the most accurate match.

Analysis – Level Vs Time

The sequence of level vs time is not particularly useful for this analysis, but we provide the following graphs to show the clean record of data and the maximum levels.

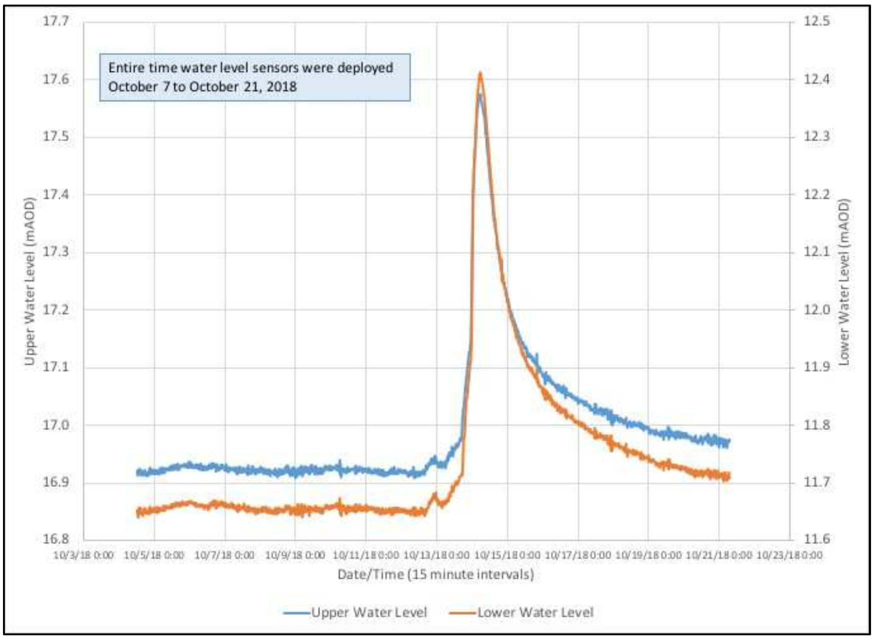

Figure 1 Water Levels Vs Date/Time (whole record)

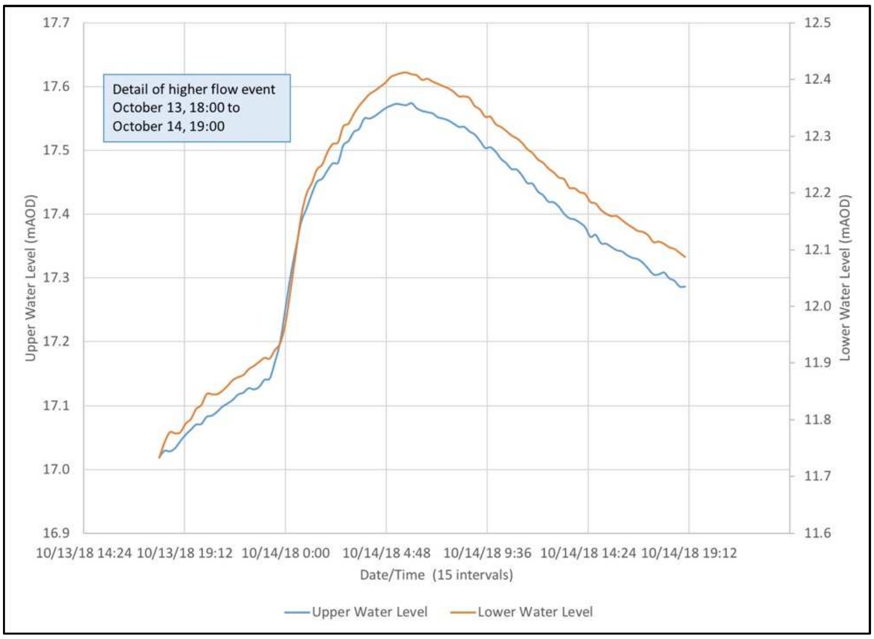

Figure 2 Water Level Vs Date/Time (detail of Peak)

We looked at the detail of the peak to see if there was a significant time shift between the upper water level (UWL) and lower water level (LWL). While it appears that UWL leads the LWL changes, the time difference did not appear to be large enough to cause significant errors, so we did not shift these two data sets relative to one another.

Analysis – Levels Vs Flow & Flow Vs Levels

The time shifted, correlated 15-minute flow and water level data was sorted by FLOW (vs time) and plotted. Catchment-area-corrected river flows at the hydropower site varied from 1.07 m^3/s to 24.5 m^3/s during the time the level sensors were deployed.

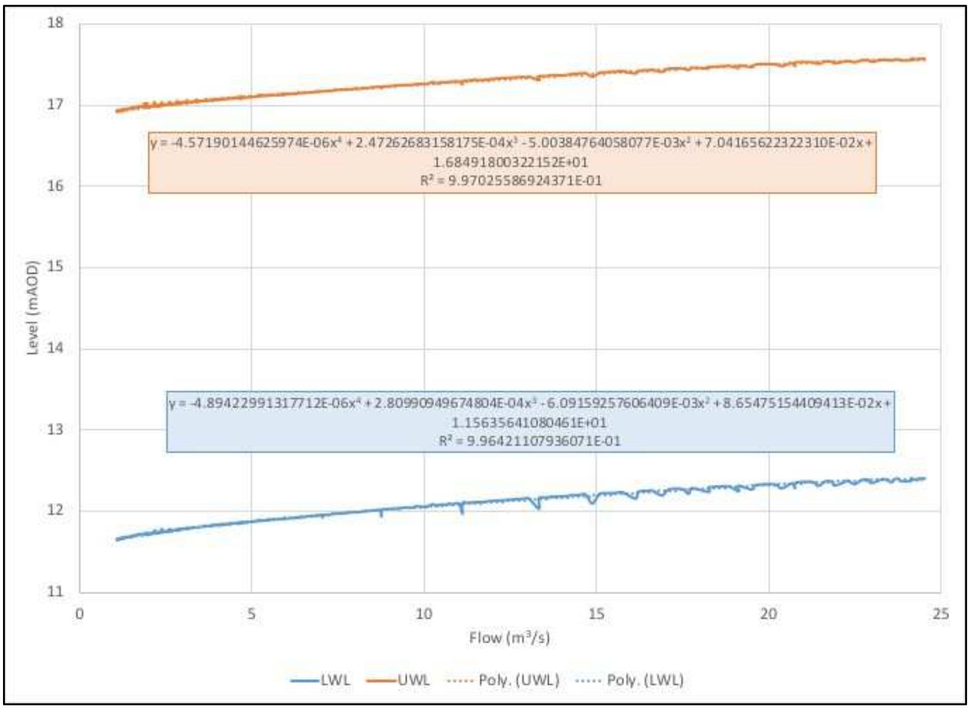

Figure 3 Levels vs River Flow

The curves above show that the UWL and LWL are relatively well behaved as a function of river flow. From Figure 3 the two equations (in easier to read form):

Equation 1: (LWL Level Vs Flow)

LWL (mAOD) = $C_6*Q^6 + C_5*n^5 + C_4*Q^4 + C_3*Q^3 + C_2*Q^2 + C_1*Q + C7$

Where;

Q = Flow in m^3/s

C6 = $-5.41681762639135 \times 10^{-8}$

C5 = $4.28806971859708 \times 10^{-6}$

C4 = $-1.32492633647586 \times 10^{-4}$

C3 = $2.04197918427546 \times 10^{-3}$

C2 = $-1.73282481513182 \times 10^{-2}$

C1 = 0.11555680533088

C7 = 11.54158561071170

Equation 2: (UWL Level Vs Flow)

UWL (mAOD) = $C_6*Q^6+ C_5*Q^5+ C_4*Q^4+ C_3*n^3+ C_2*Q^2+ C_1*Q+ C7$

Where;

Q = Flow in m^3/s

C6 = $-5.88103528167960 \times 10^{-8}$

C5 = $4.67728557372098 \times 10^{-6}$

C4 = $-1.44357016925490 \times 10^{-4}$

C3 = $2.18408839703581 \times 10^{-3}$

C2 = $-1.74049367574663 \times 10^{-2}$

C1 = 0.10251538003174

C7 = 16.8248237829488

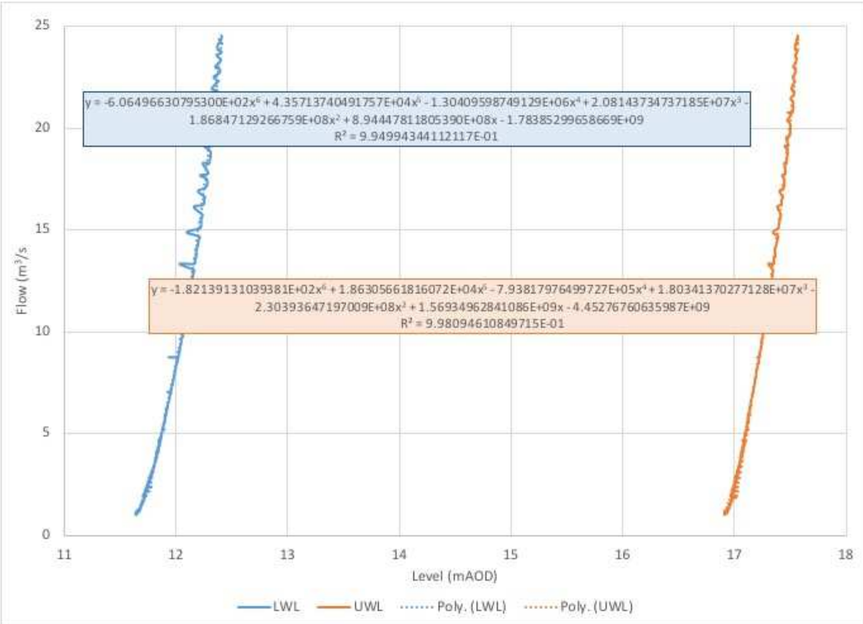

Figure 4 River Flow Vs Levels

Figure 4 is simply the invert of Figure 3, but equations from both can be used for the control system.

From Figure 4 the two equations (in easier to read form):

Equation 3: (Flow Vs LWL Level)

Q (flow) = C_6*LWL^6+ C_5*LWL^5+ C_4*LWL^4+ C_3*LWL^3+ C_2*LWL^2+ C_1*LWL+ C7

Where;

LWL = Lower Water Level (mAOD)

C6 = $-6.06496630795300 \times 10^{2}$

C5 = $4.35713740491757 \times 10^{4}$

C4 = $-1.30409598749129 \times 10^{6}$

C3 = $2.08143734737185 \times 10^{7}$

C2 = $-1.86847129266759 \times 10^{8}$

C1 = $8.94447811805390 \times 10^{8}$

C7 = $-1.78385299658669 \times 10^{9}$

Equation 4: (Flow Vs UWL Level)

Q (flow) = C_6*UWL^6+ C_5*UWL^5+ C_4*UWL^4+ C_3*UWL^3+ C_2*UWL^2+ C_1*UWL + C7

Where;

UWL = Upper Water Level (mAOD)

C6 = $-1.82139131039381\times10^{2}$

C5 = $1.86305661816072\times10^{4}$

C4 = $-7.93817976499727\times10^{5}$

C3 = $1.80341370277128\times10^{7}$

C2 = $-2.30393647197009\times10^{8}$

C1 = $1.56934962841086\times10^{9}$

C7 = $-4.45276760635987\times10^{9}$

Analysis – Flow Duration Curve

To create equations of water levels vs river flow in terms of Qn it is necessary first to develop an equation that models flow and Qn. This curve is called the Flow Duration Curve (FDC) and is typically graphed with Qn (% of year that flow exists) along the X axis with the flow along the vertical or Y axis. For purposes of the equation we require it is more useful to invert these axes. The graph below is from the long record of daily average flows (adjusted for the reduced catchment as described above).

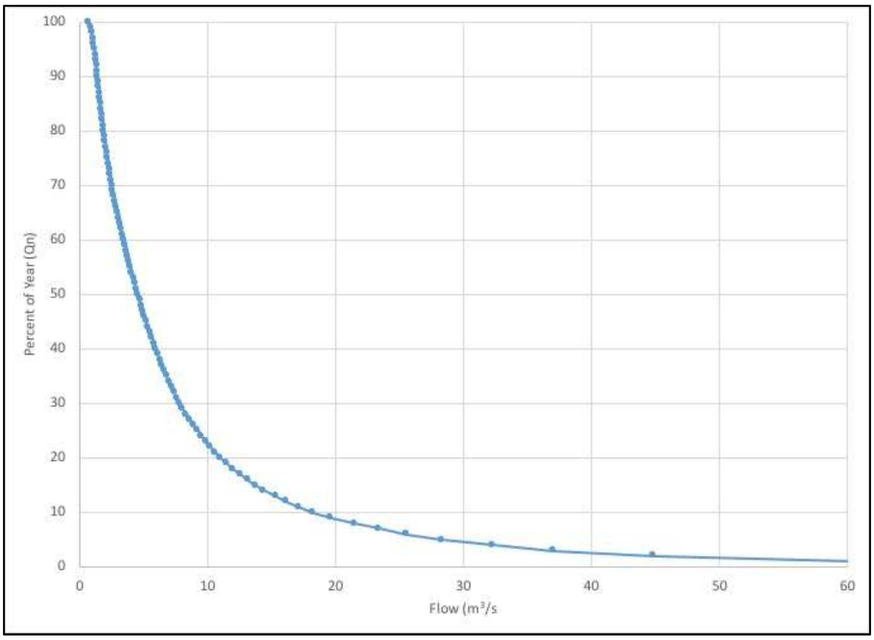

Figure 5 Inverted Flow Duration (Q99 to Q1)

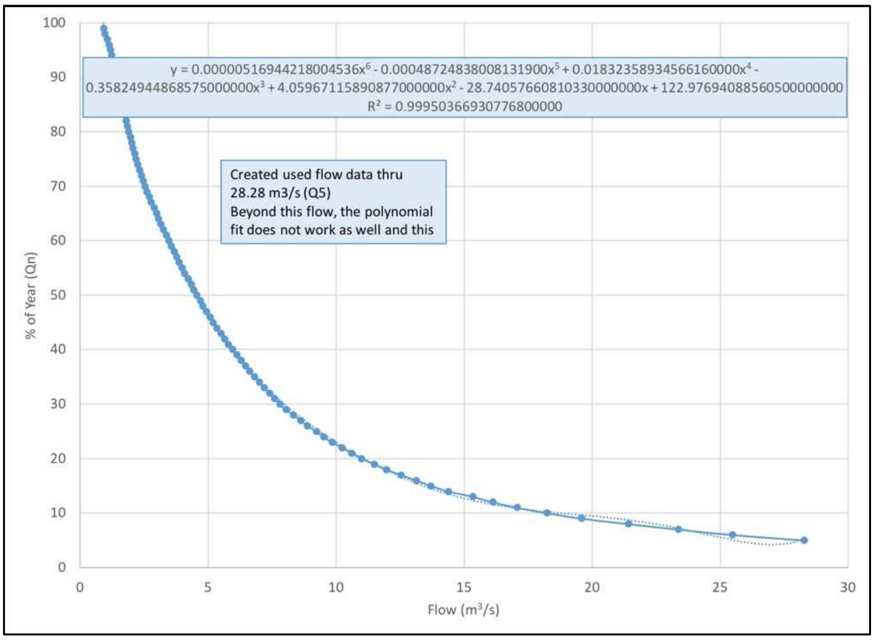

Figure 6 Inverted Flow Duration with Curve Fit (to Q7)

Figure 6 above is a detail of the full inverted "flow duration curve" ranging from Q99 to Q5. A 6th order polynomial (with 14 significant figures) was used to fit the data. The range of the graph was limited to Q5 for two reasons:

- This encompassed all the flow data from when the level sensors were deployed
- If Qn values to higher flows were included, the quality of the curve fit decreased.

Equation 5: (Qn Vs Flow)

$$Qn = C_6{*}Q^6 + C_5{*}Q^5 + C_4{*}Q^4 + C_3{*}Q^3 + C_2{*}Q^2 + C_1{*}Q + C7$$

Where;

Q = Flow in m^3/s

C6 = $5.16944218004536 \times 10^{-06}$

C5 = $-4.87248380081319 \times 10^{-04}$

C4 = $1.83235893456616 \times 10^{-02}$

C3 = -0.358249449

C2 = 4.059671159

C1 = -28.74057661

C7 = 122.9769409

Analysis – Levels Vs Qn & Qn Vs Level

The flow numbers in Figure 3 above were replaced with Qn values using EQUATION 1. This was then graphed two ways, Levels Vs Qn and Qn Vs Levels. Curve Fits (6th order polynomials) were developed for all the curves (for UWL and LWL for both graphs)

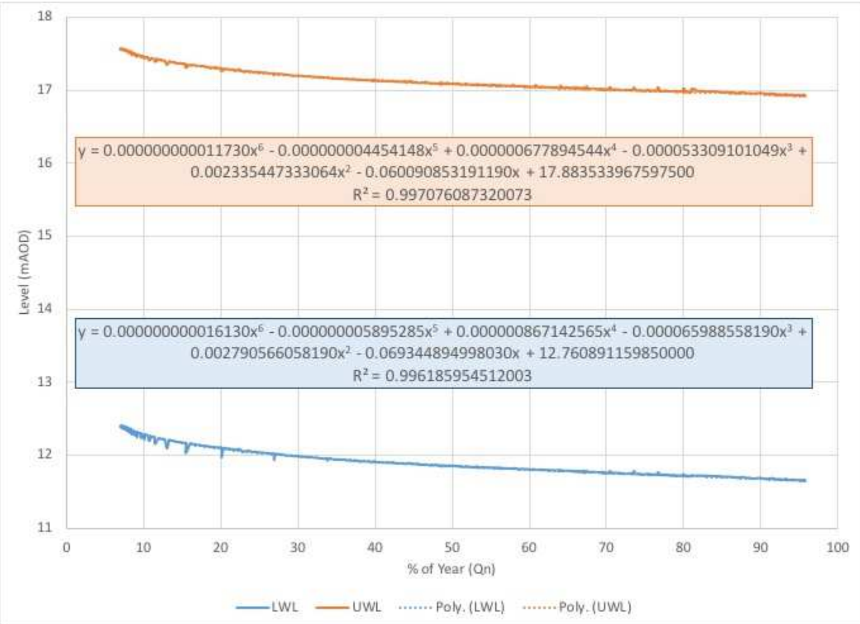

Figure 7 Level Vs Qn

From Figure 7 the two equations (in easier to read form):

Equation 6: (LWL Level Vs Qn)

LWL (mAOD) = $C_6*Qn^6 + C_5*Qn^5 + C_4*Qn^4 + C_3*Qn^3 + C_2*Qn^2 + C_1*Qn + C7$

Where;

Qn = % of year this flow or higher exists

C6 = $1.1730336808239 \times 10^{-11}$

C5 = $-4.45414817538679 \times 10^{-9}$

C4 = $6.77894544104581 \times 10^{-7}$

C3 = $-5.33091010492493 \times 10^{-5}$

C2 = $2.335447333064040 \times 10^{-3}$

C1 = $-6.009085319118950 \times 10^{-2}$

C7 = 17.8835339675975

Equation 7: (UWL Level Vs Qn)

UWL (mAOD) = C_6*Qn^6+ C_5*Qn^5+ C_4*Qn^4+ C_3*Qn^3+ C_2*Qn^2+ C_1*Qn+ C7

Where;

Qn = % of year this flow or higher exists

C6 = $1.613020475651690\text{E}\times10^{-11}$

C5 = $-5.895284843839260\times10^{-9}$

C4 = $8.67142564550959\times10^{-7}$

C3 = $-6.59885581903462\times10^{-5}$

C2 = $2.79056605819035\times10^{-3}$

C1 = $-6.93448949980296\times10^{-2}$

C7 = 12.76089115985

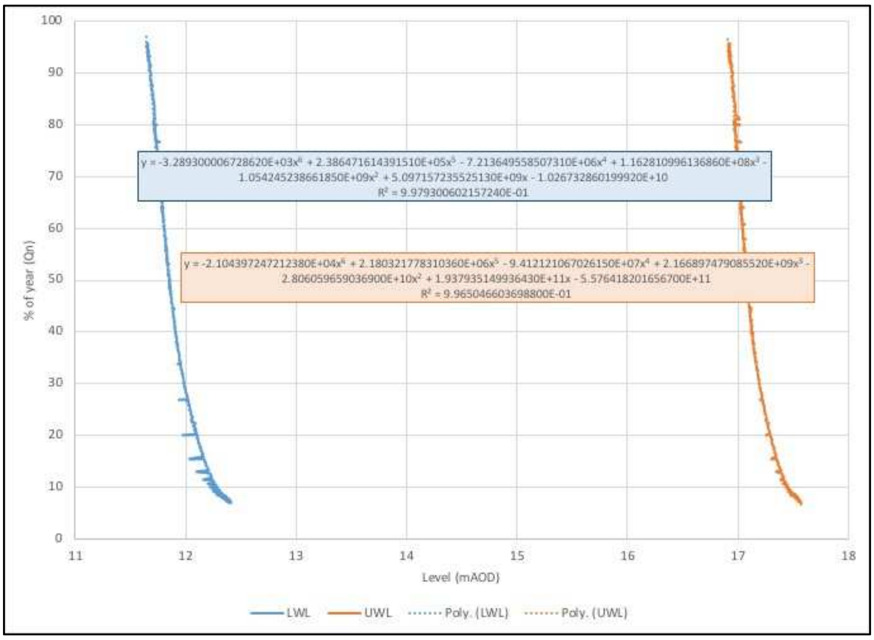

Figure 8 Qn Vs Level

Figure 8 is simply the invert of Figure 7, but equations from both can be used for the control system.

From Figure 8 the two equations (in easier to read form):

Equation 8: (Qn Vs LWL Level)

$Qn = C_6*LWL^6 + C_5*LWL^5 + C_4*LWL^4 + C_3*LWL^3 + C_2*LWL^2 + C_1*LWL + C7$

Where;

LWL = Lower Water Level (mAOD)

C6 = $-3.28930000672862 \times 10^3$

C5 = $2.38647161439151 \times 10^5$

C4 = $-7.21364955850731 \times 10^6$

C3 = $1.16281099613686 \times 10^8$

C2 = $-1.05424523866185 \times 10^9$

C1 = $5.09715723552513 \times 10^9$

C7 = $-1.02673286019992 \times 10^{10}$

Equation 9: (Qn Vs UWL Level)

$Qn = C_6*UWL^6 + C_5*UWL^5 + C_4*UWL^4 + C_3*UWL^3 + C_2*UWL^2 + C_1*UWL + C7$

Where;

UWL = Upper Water Level (mAOD)

C6 = $-2.10439724721238 \times 10^4$

C5 = $2.18032177831036 \times 10^6$

C4 = $-9.41212106702615 \times 10^7$

C3 = $2.16689747908552 \times 10^9$

C2 = $-2.8060596590369 \times 10^{10}$

C1 = $1.93793514993643 \times 10^{11}$

C7 = $-5.5764182016567 \times 10^{11}$

System Control/Flow Split

Proportional Take Operation of the System (50/50, Q75)

The hydropower system is a "run-of-river" system which creates a depleted reach. In this circumstance the EA requires that the scheme must leave a variable flow in the depleted reach which is quantified on the basis of a percentage proportion having already allowed a permanent minimum residual of "Hands-Off" flow (HOF). Above the HOF condition, the flow through the hydropower system is proportional to the additional river flow. For this particular system we are proposing a 50/50 flow split or proportional take (of available river flow) with a minimum bypass (stays in river) of Q75. In other words, the bypass flow (which stays in the river) is this Q75 minimum, PLUS 50% of the available flow above this minimum. Furthermore, the size of the hydropower system is constrained to a maximum flow capacity of 2.9 m^3/s; so the 50% which is theoretically available to be taken by the hydro is capped at this amount.

To give an example:

Q75 = 2.18 m^3/s (minimum flow that MUST stay in the river)

At Q20, the river flow = 11 m^3/s

The actual flow that must stay in the river = 2.18+(11-2.18)*50% = 6.59 m^3/s

Therefore, at Q20, the system WOULD BE PERMITTED to use 11-6.59 = 4.41 m^3/s

BUT the max hydropower flow capacity is 2.9 m^3/s, so that's all the system will actually use.

Furthermore, there is also a minimum start-up flow which is technically required to make the hydropower system operate. This means that, although the proposed system must then retain a residual (bypass) flow equivalent to Q75 in the river, in practice the relationship described above would really result in the hydropower system not starting until some even higher flow. To reach this threshold, there is the minimum bypass flow (Q75) plus 2x the start-up flow (since any flows above Q75 are split between the residual and the hydropower system.

If the system start-up flow is assumed to be at least 5% of its peak flow capacity, at Guyzance the system will NOT start until the river flow rises to Q70. Hence Q75 is NOT the start-up point.

Control System (electrical)

The hydropower scheme control system includes a PLC (Programmable Logic Controller) to program and execute all aspects of system control. The PLC constantly monitors input from electronic water level sensors. If this input is lost, or the signal infringes any agreed parameters (e.g. minimum level), the system ceases operation.

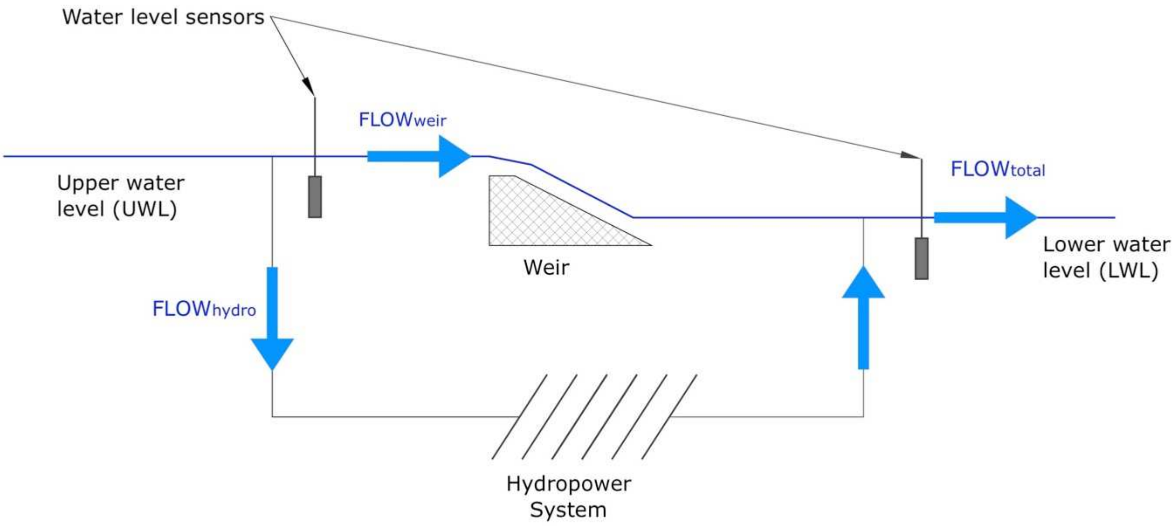

Figure 9 Proportional Take/Sensor System

Figure 9 shows the system/site schematically. At the intake, there is a calibrated water level sensor (mAOD).

A water level sensor is also depicted at the discharge of the hydropower system. Where installed, data obtained from this sensor is not necessary to the control logic which maintains compliance with the flow regime, but is used in other functions (efficiency monitoring etc).

Control Logic (using developed equations and sensor)

The control system must monitor flows and use information from a sensor to turn on, increase flow or decrease flow through the hydropower system as required to meet the guidelines of the 50/50 proportional take with minimum bypass flow = Q75 river flow. In Figure 9:

FLOWtotal = total river flow (also the sum of Fhydr+Fweir)
FLOWhydro = flow through the hydropower system
FLOWweir = bypass flow

Equation 4 above (Flow Vs UWL) takes the UWL sensor reading and returns a value for the flow which is currently passing down the main channel.

The minimum residual flow (river flow at Q75) and the 50/50 proportional take define the residual flow that must be maintained (at the calculated river flow).

The system records what flow it is taking at any given time, and records (from the previous step above) what flow is in the main channel, and sums these to record the total flow, at any given time. What flow the system is permitted to use in that condition is the difference between the total flow and the required residual flow in that condition. This difference is constantly checked in order to determine that the system is not exceeding the constraints of the regime.

Once the system is running at maximum speed, it is taking its maximum flow. Therefore the additional unused flow will augment the residual flow which will increasingly exceed the maximum system capacity.

Whichever case holds, whenever the system flow is between start-up and maximum, the calculated value for residual flow would be plugged into Equation 2 (UWL Level Vs Flow) which will then return a value for the required upper water level (UWL) to meet that target residual flow. The system will then increase or decrease its flow to maintain the target UWL.

If the system is already running at maximum, it will cease to control the UWL which will simply rise further with any further increase in flow.

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Version control

31.10.2018 first issue - prior to data retrieval

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31.10.2018

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31.10.2018

Executive summary

This document describes how water level data is gathered at site in 2018 and referenced to Qn values derived from the simultaneous flow data from the Morwick gauging station, in order to illustrate the naturally-occurring water levels at the intake to the new scheme - this being the upper limit of the depleted reach which is affected by the proposed changed flow regime. The data allows an equation to be formulated which will serve as the basis for the programmed control logic under which the hydropower scheme will operate. This method has been operating successfully for some years in other UK schemes (e.g. Aberdeen Community Energy scheme at Donside; Brahan Estate).

Data gathering

A submerged pressure sensor was deployed at the location of the proposed intake. Data was gathered for the period of 8th October to 5th November 2018.

Data analysis

The sequence of submersion depth data is converted to water levels in mAOD using site datum reference. The sequence is then graphed and overlaid on a graph of the same events seen in the 15-minute flow data sequence from the Morwick gauging station, to adjust for time elapsed between measuring locations. The Morwick flow values for this period are then assigned Qn percentile values based on analysis of the longer-term Morwick dataset (as above). Each corresponding value of measured water level is then assigned a Qn value. For each measurement point, the dataset is then ordered and graphed to produce a trendline equation of the relationship between water level and main river flow. A second equation is then derived for water level at each Qn IF the screw is taking its flow as per agreed regime.

Application of the data to the system control logic

The hydropower scheme control system includes a PLC (Programmable Logic Controller) to program and execute all aspects of system control. The PLC constantly monitors input from an electronic water level sensor at the hydropower intake. If this input is lost, or the signal infringes any agreed parameters (e.g. minimum level), the system ceases operation.

At all times when the water level input is being received, the PLC continuously applies the above equation to calculate the flow in the main channel of the river. Inputs occur many times per second. The PLC checks an agreed parameter to decide when the system may start abstracting, sets screw speed to take a specific flow, continuously checks the second equation to confirm that total flow (river + turbine) is compliant with the instantaneous water level, adjusts the speed up or down to suit, and continuously repeats this process.

Results - dataset and equation

The data will be recovered and processed by mid November 2018, at which point the equation will be derived and the data presented. The data shows what the water levels have been without the scheme operating, and what water levels will be for each value of Qn when the scheme is allowed to operate under the proposed flow regime.