DAMAGE TO FISH IN KAPLAN-TYPE HYDRO TURBINES

A THEORETICAL STUDY

COMMISSIONED BY ENVIRONMENT AGENCY (UK)

Status report	:	draft
Date report	:	05-02-2021
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BE Engineering

1. RECONSTRUCTION OF HYDRO TURBINE CONTROL

Question:
Can a turbine’s control strategy be reconstructed based on its dimension, shape and position of the runner and the inlet guide vanes (IGV)?

Given:

- *dimension, shape, and position of IGV*
- *dimension and position of runner*
- *operating range in terms of flow rate and net head*

Control parameters:

- *inlet guide vane (IGV) opening angle* α
- *runner speed* N
- *runner blade opening angle* β

Two examples of double-regulated turbines are studied in this report: a run-of-river, bulb turbine (fig. 1) and a Kaplan turbine. Data on a Kaplan turbine was provided by DerwentHYDRO.

The reconstruction of turbine control is based on maximum energy extraction while meeting the condition that the swirling inlet flow matches the runner blade angles.

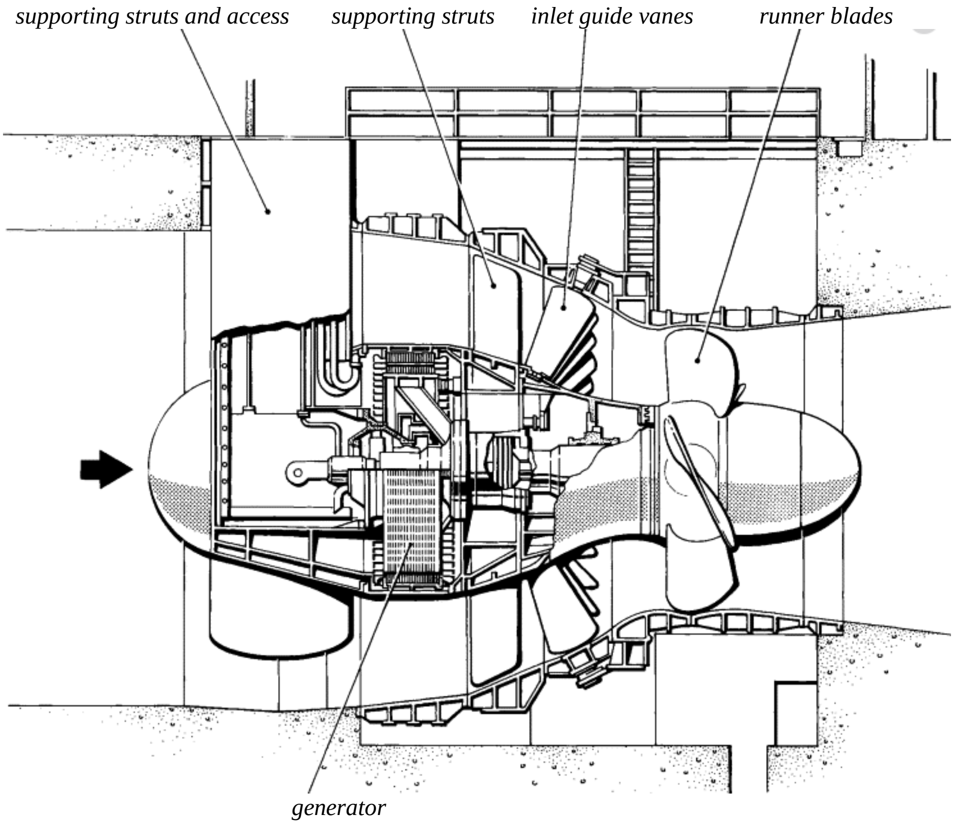


Figure 1: Drawing of a bulb turbine.

1.1 BULB TURBINE

This bulb turbine design has adjustable IGV, a fixed runner speed, and adjustable runner blades. The hillchart in fig. 2 shows the two control parameters: guide vane opening angle α *and runner blade opening angle* β *in the entire operating range. Performance (net power and efficiency) are shown as well.*

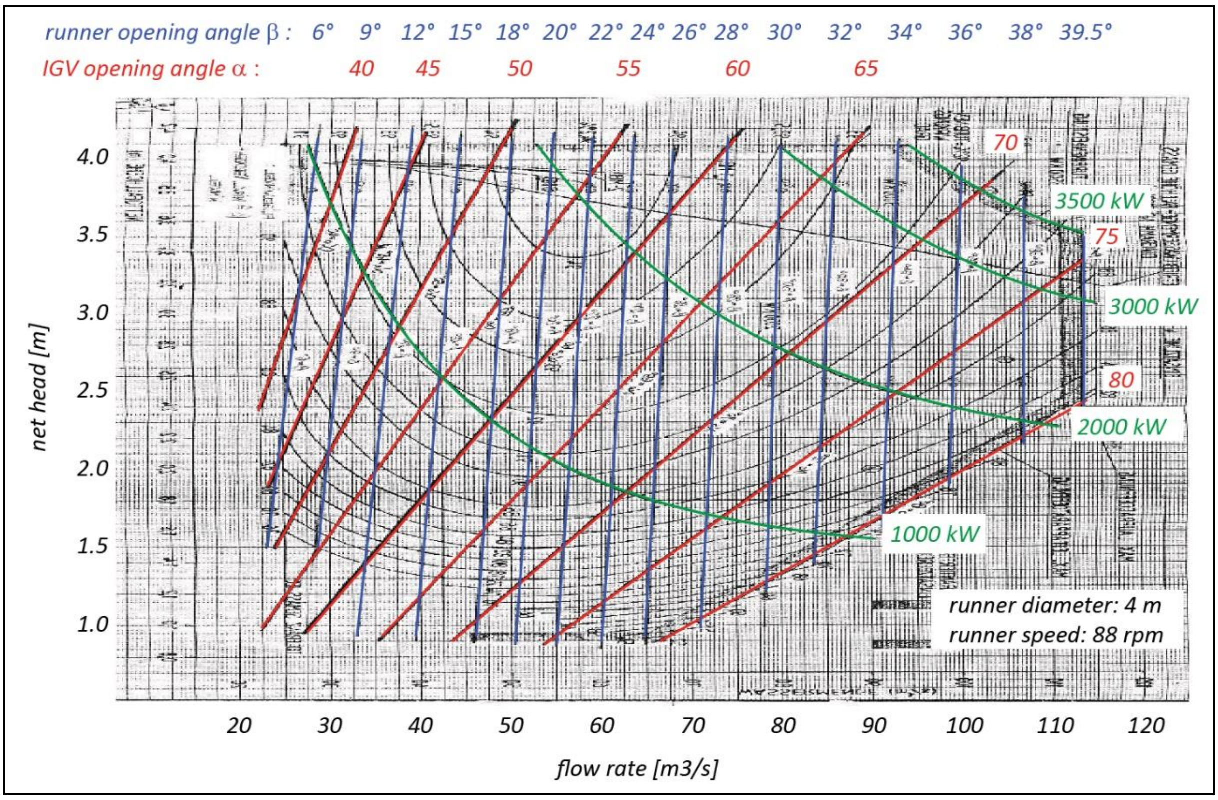


Figure 2: Hillchart of control and performance of the double-regulated bulb turbine.

First, the optimum IGV opening angle is calculated for the entire operating range of the turbine. This calculation assumes that the average angular momentum of the swirling flow thus created, can be used in the runner to convert the net, available head to power (fig. 3). What is required for the calculation is the shaft speed of the runner and the shape, dimension, and position of the IGV. It turns out the reconstructed IGV opening angle α *is in good agreement with the hillchart of the real turbine in fig. 2.*

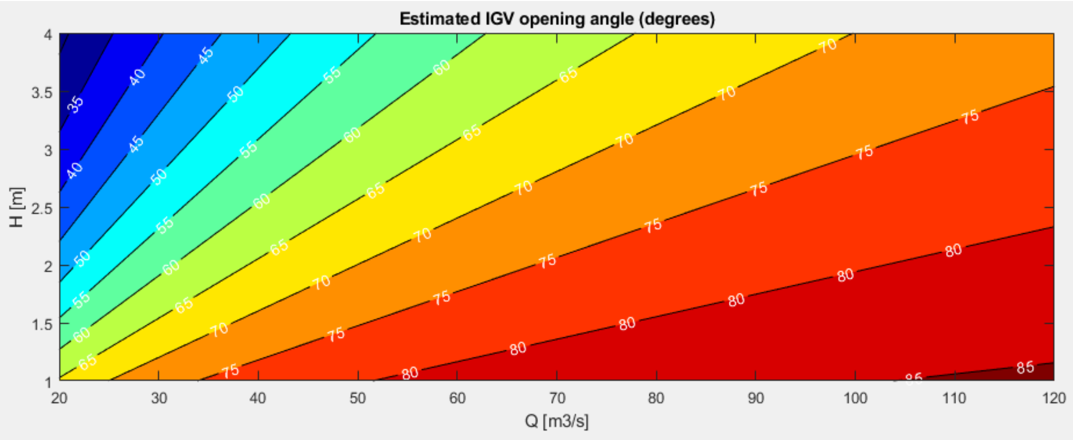


Figure 3: Reconstruction of optimum IGV opening angles α *for the bulb turbine.*

Next, the opening angle of the runner blades is estimated. The dimension and the position of the runner is known, as is the runner speed. The IGV angles of fig. 3 are used to compute the swirl distribution of the flow. It is assumed that the runner blade opening angle matches the angle of the swirling flow that approaches the *runner. Since a runner blade cannot match the flow along its entire span in the full operating range, the blade is set to match the flow at 70% of its span. This is approximately where the contribution to the torque is maximal. The reconstructed runner blade opening angles are shown in fig. 4. These values are fairly close to the angles β in the hillchart of fig. 2, specially near the design point at Q = 60 m^3/s and H = 4 m.*

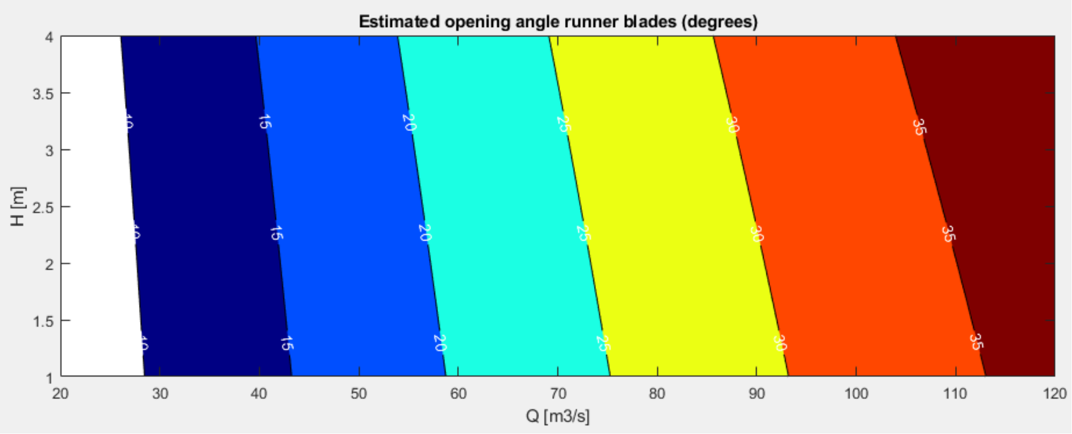


Figure 4: Reconstruction of runner blade opening angles β for the bulb turbine.

The swirling flow leaving the IGV contains a gross power that is transferred to electrical power by the runner. This gross power can be estimated based on the guide vane settings of fig. 3. The result is given in fig. 5 and can be compared to the net power in the hillchart of fig. 2. The trend agrees although the net power is lower, of course, because of hydraulic losses in the runner, mechanical losses in the drive train and electrical losses in the generator. At 50 m^3/s and a head of 4 m the efficiency is near its maximum of 94.2% and the net power is nearly equal to the estimated gross power of 2000 kW.

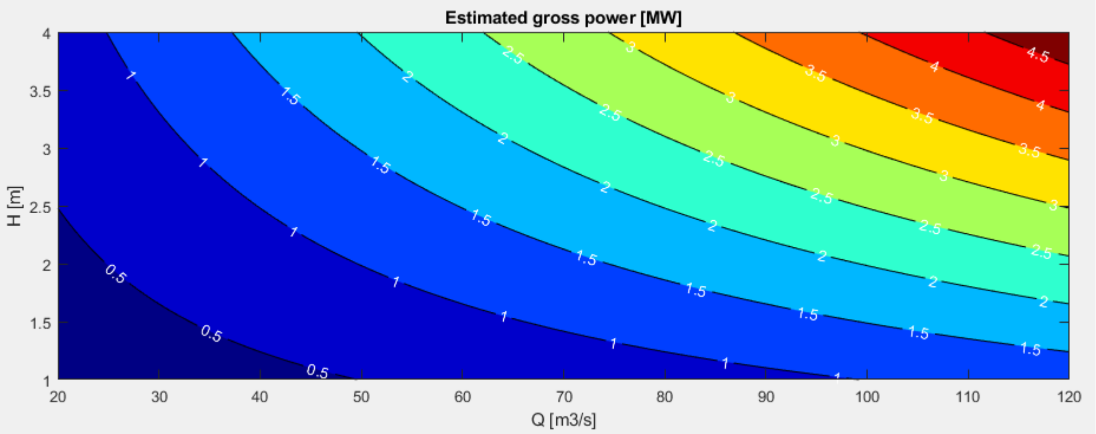


Figure 5: Reconstruction of gross power contained in the swirling flow, for the bulb turbine.

1.2 DerwentHYDRO KAPLAN TURBINE

Figure 6 shows the layout of a Kaplan turbine provided by DerwentHYDRO. The supposed performance is given in figure 7 as a Hill chart for a range of flow numbers Φ and specific energy numbers (or head numbers) Ψ. The design point of this turbine is at $\Phi = 0.215$ and $\Psi = 0.335$, where dimensionless numbers are defined as

$$\Phi = \frac{4Q}{\pi^2 N D^3} \quad and \quad \Psi = \frac{2gH}{\pi^2 N^2 D^2}$$

All quantities are in S.I units, but shaft speed N is in rev/s. The specific speed N_S of a turbine is defined as

$$N_S = \frac{2\pi N\sqrt{Q}}{(gH)^{\frac{3}{4}}}$$

The value of the specific speed N_S can be computed from Φ and Ψ as

$$N_S = 2^{\frac{3}{4}}\sqrt{\pi}\,\frac{\Phi^{\frac{1}{2}}}{\Psi^{\frac{3}{4}}} = \mathbf{3.14}$$

As an example: this turbine, with a runner diameter of 1 m (fig. 6) running at 250 rpm, would operate at its design point at a flow rate Q = 2.21 m^3/s and a head H = 2.93 m.

This Kaplan turbine design has adjustable IGV, a fixed runner speed, and adjustable runner blades. The Hill chart in fig. 7 shows the two control parameters: guide vane opening A0 and runner blade (tip) opening angle b (or β) in the entire operating range. Isocurves of efficiency are shown as well.

Again (like in section 1.1) the optimum IGV opening angle is reconstructed for the entire operating range of the turbine based on the requirement that the angular momentum of the swirling flow be equal to the specific energy gH available. What is required for the calculation is the shaft speed of the runner and the shape, dimension, and position of the IGV. What complicates matters is that the Hill chart in fig. 7 does not show the IGV opening angle α but, instead, a nondimensional measure of the guide vane opening, A0.

The guide vane opening A0 is defined as

$$A0 = \frac{z.\,a\mathbf{0}}{D_{IGV}}$$

with z the number of IG vanes, a0 the shortest distance between two neighbouring vanes (in mm), and D_{IGV} the pitch diameter of the IGV (in mm). For the Kaplan turbine in fig. 6, z = 18 and D_{IGV} = 1300 mm. The distance a0 is measured from figure 8 by manually setting the vanes at a range of different guide vane angles α. The result is given in figure 9 and is used to convert the vane openings A0 in the Hill chart of fig. 7 to IGV angles α.

Derwent*HYDRO*

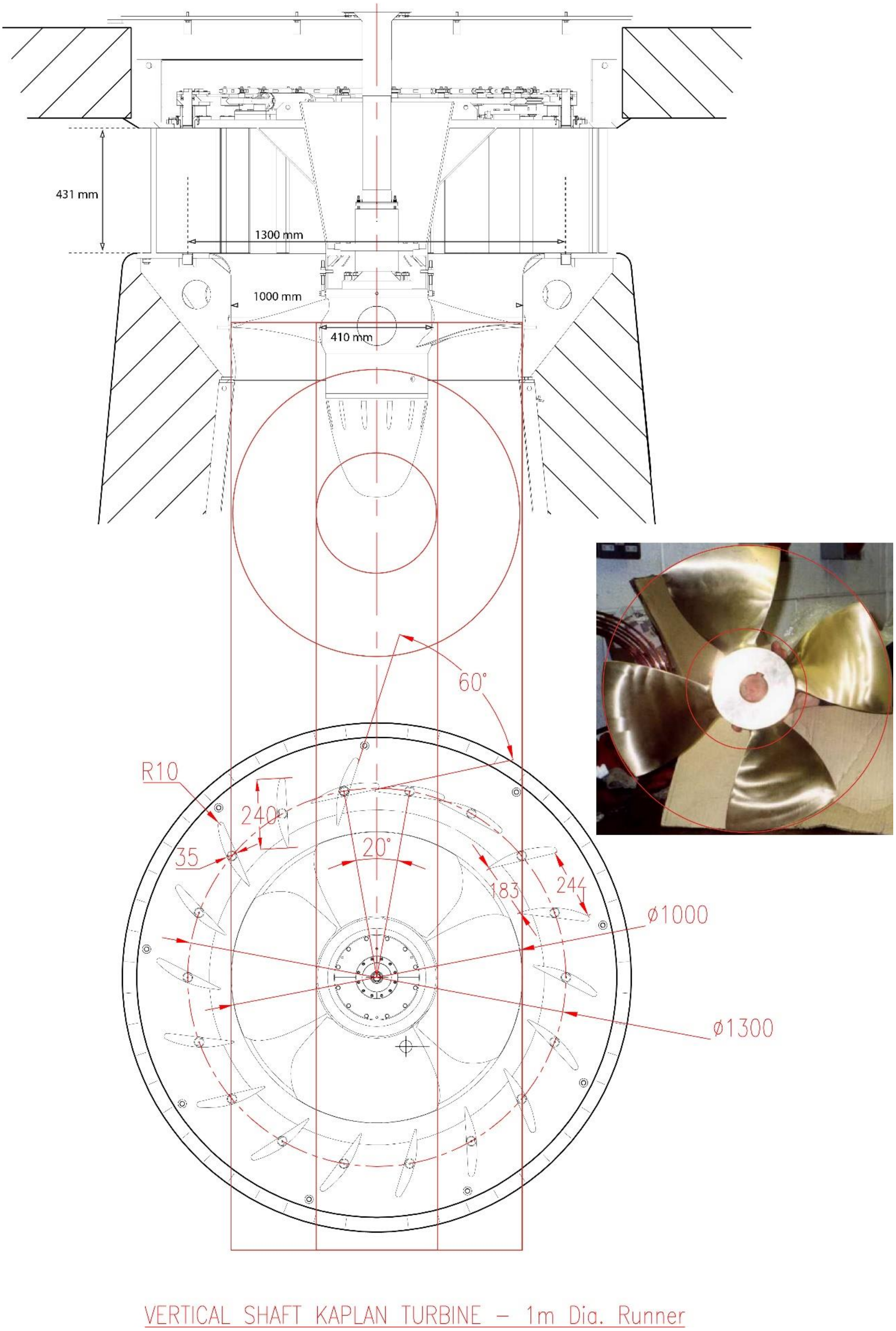


Figure 6: Kaplan turbine provided by DerwentHYDRO – based on Longbridge Hydro. The photograph shows a Kaplan runner with a somewhat smaller hub diameter.

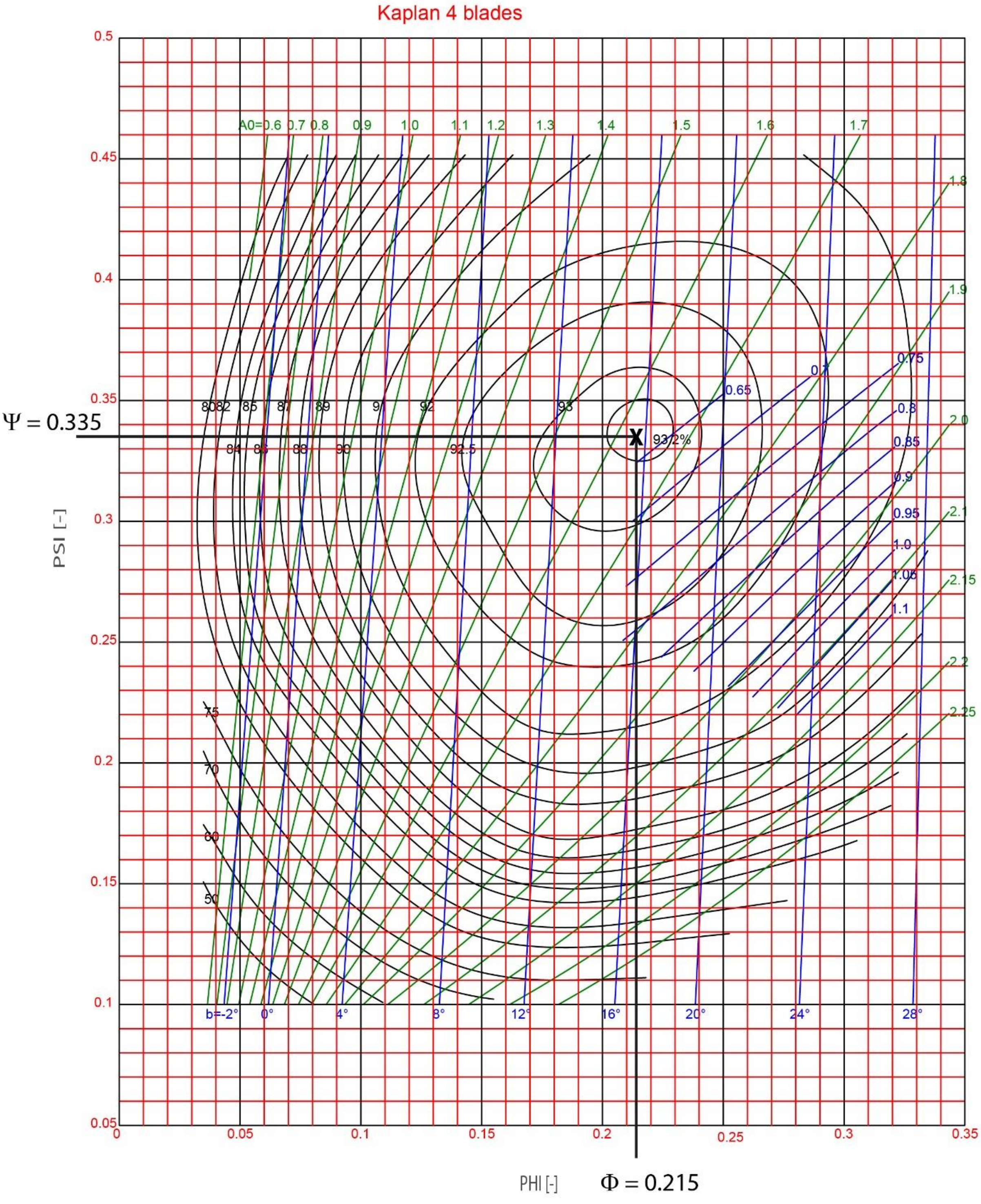


Figure 7: Hill chart presumably of the Kaplan turbine in figure 6, with PHI the flow number Φ, PSI the head number Ψ, A0 a measure of the guide vane opening, and b the runner blade opening angle β at the tip of the blades.

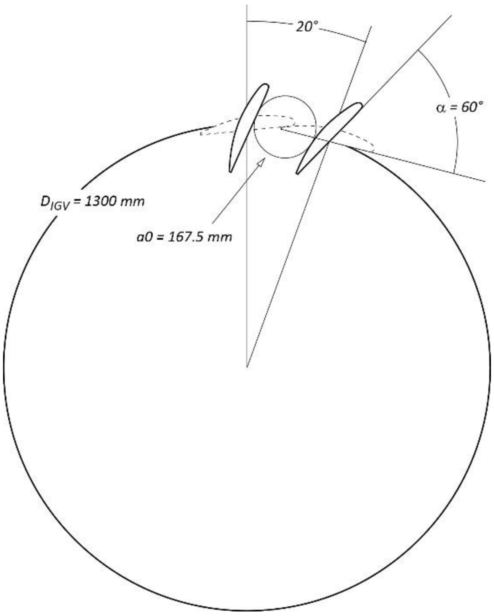


Figure 8: Drawing used to measure a0.

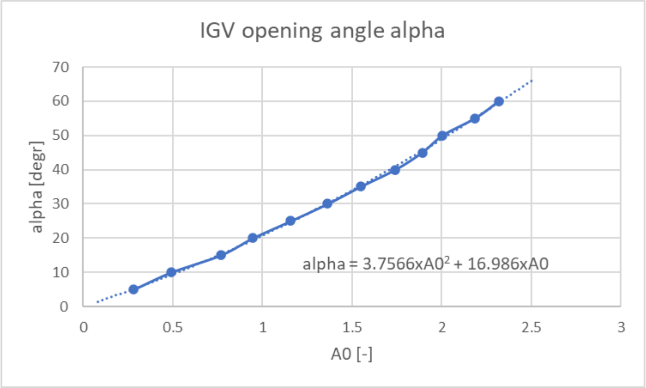


Figure 9: Graph to convert values of A0 to IGV angle α.

The reconstructed values for the optimum IGV angles are presented in figure 10 as a coloured overlay. Several A0-values in the Hill chart are converted to α*-values to enable comparison with the reconstruction. It shows that IGV angles can be reconstructed to within a few degrees. This is accurate enough to serve as a basis for subsequent estimations of fish damage.*

The runner blade angles β *can also be reconstructed from the dimensions of runner and IGV. The calculation is based on the estimated IGV angles of figure 10 and the results are presented in figure 11. It shows that estimated* β*-values are quite good, although the trend is slightly different. The agreement at the design point of the turbine is spot on with blade tip angle* β *= 16°.*

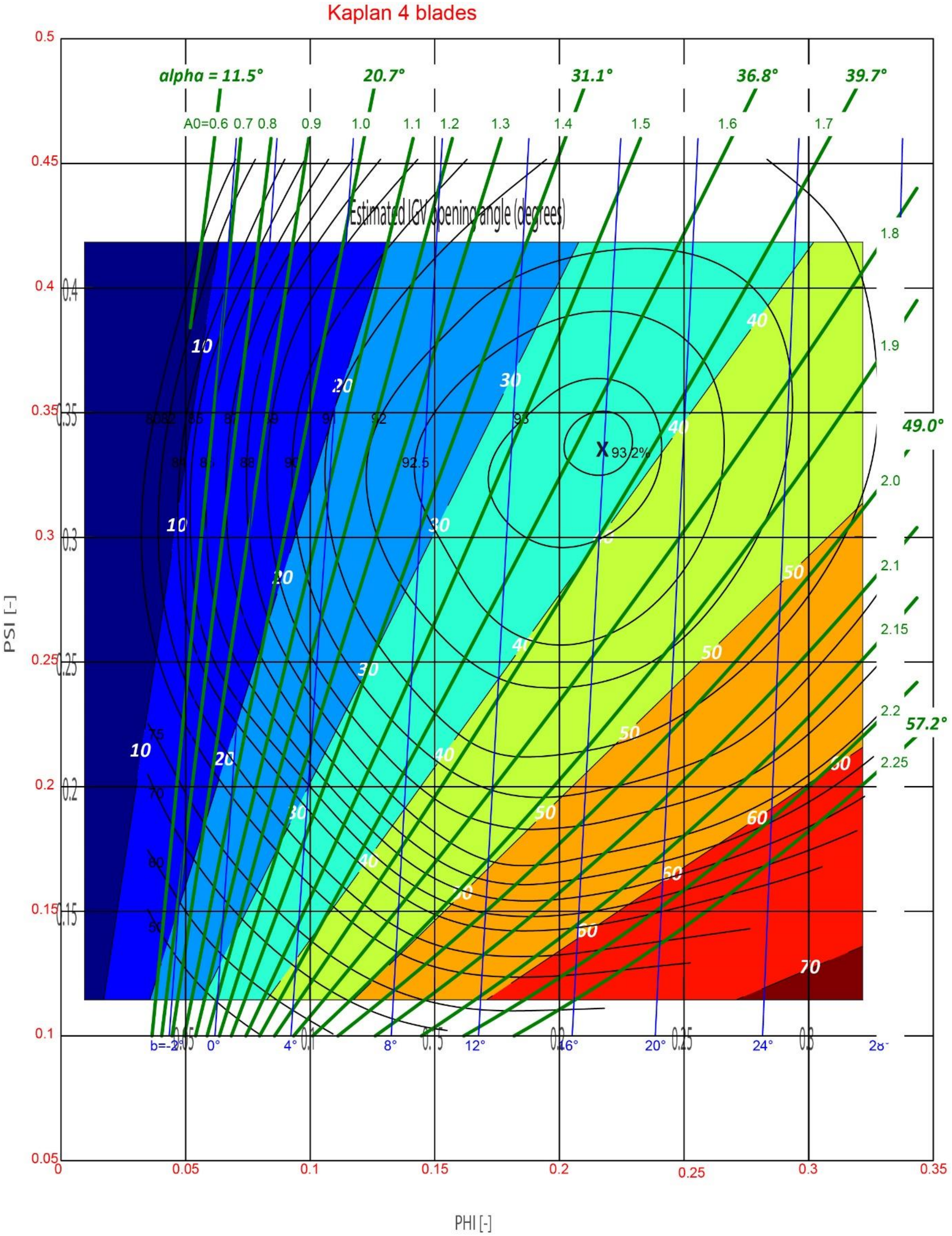


Figure 10: Copy of the Hill chart of figure 7 showing iso-curves of guide vane opening A0 (and angle α) as green curves. Reconstructed values of the IGV opening angle α are added as a colour map.

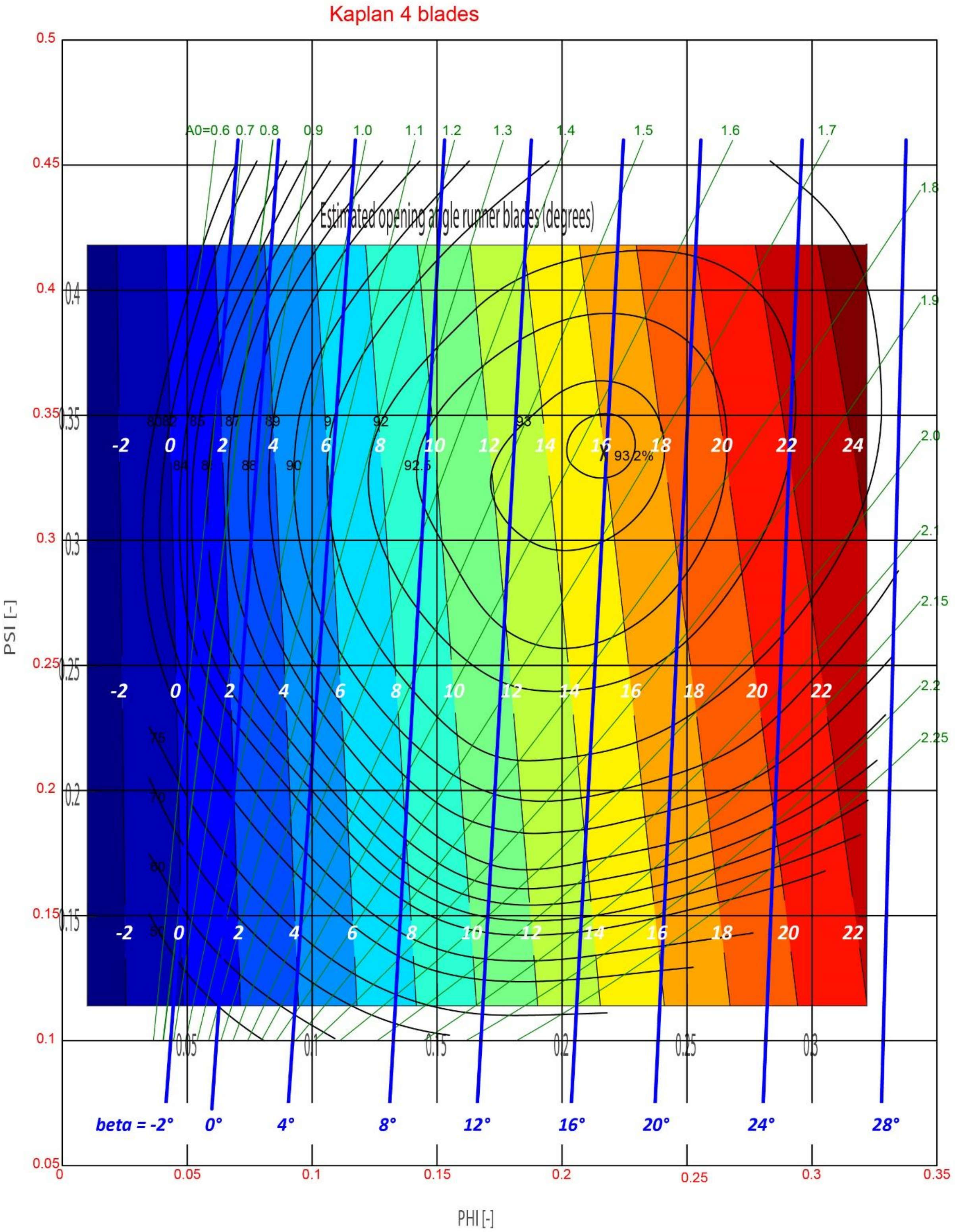


Figure 11: Copy of the Hill chart of figure 7 showing iso-curves of blade tip opening angles β as blue curves. Reconstructed values of the blade tip opening angle β are added as a colour map.

2. BHA HYDROPOWER SCHEMES

Data of four hydropower schemes appropriate in the UK context were provided by BHA (table 1). All four turbines are double-regulated with adjustable IGV, a fixed runner speed, and adjustable runner blades. HPS Sorne Castle is different from the other three in that its runner blades are actually fixed during operation. It needs an overhaul to manually set the blades to a different angle.

The design point (or the rated point) of a turbine is the operating point at maximum efficiency. This best efficiency point is assumed to occur at a rated flow rate Qr of 70% Q_{max}*, at the rated head H and shaft speed N. With this estimated flow rate Qr, the values for the dimensionless flow number* Φ*, head number* Ψ*, and specific speed* N_S *are computed. It turns out that all 4 turbines have very similar designs. Values for* N_S *put them in the range of high specific speed Kaplan turbines. HPS Sorn Castle is again different from the other three in its IGV design. In addition, this turbine is operated at 250 rpm rather than at its design speed of 375 rpm.*

The value of the specific speed N_S *allows one to estimate the runner diameter D. Well-designed turbomachines are known to follow the so-called Cordier diagram. A linear regression on Cordier's data for high- specific speed machines gives*

$$D_S = \left(\frac{8.26}{N_S}\right)^{0.517} \quad for \quad N_S > 0.85$$

with specific diameter D_S *defined as*

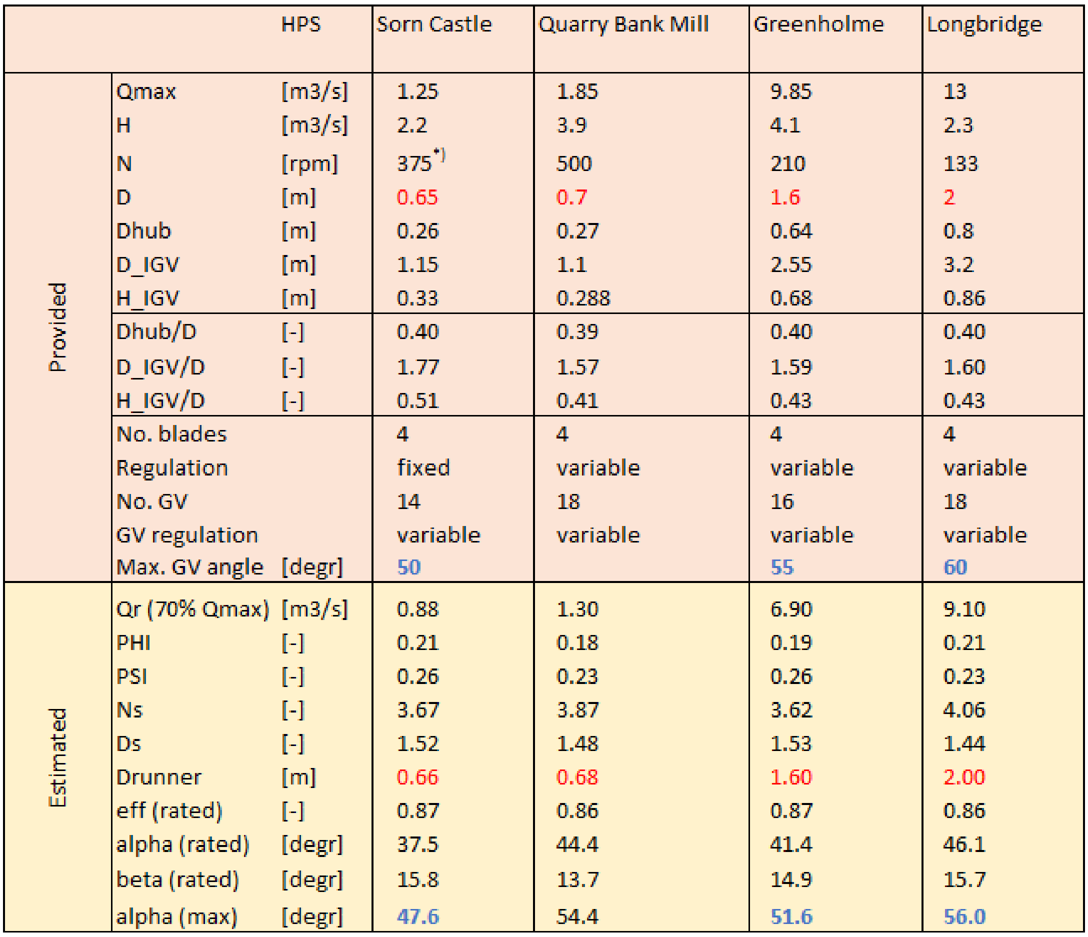
$$D_S = D\frac{(gH)^{\frac{1}{4}}}{\sqrt{Q}}$$

Values for the runner diameter thus estimated are also given in table 1. It shows that the estimated runner diameters D_{runner} *are very close to the actual ones (both values indicated in red).*

The GV opening angle α *and the runner blade opening angle* β *are also estimated at the rated operating point. It shows that the GV opening angle of Sorn Castle is relatively small compared to the other three turbines.*

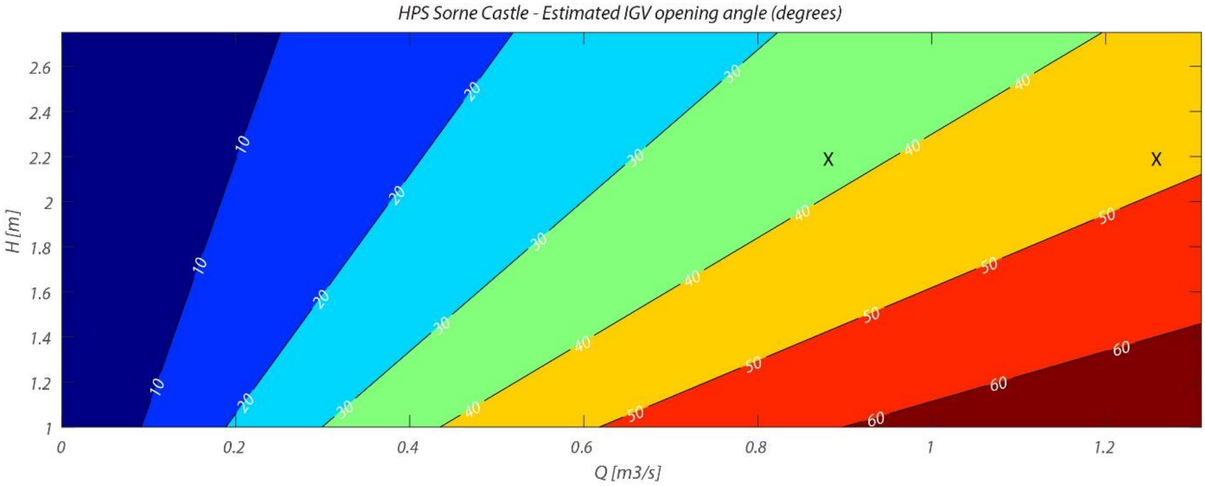
The estimated GV opening angle at maximum flow rate Q_{max} *is also given in the table. These values are consistent with the values provided by BHA (both values indicated in blue).*

The IGV control in the entire operating range of the four turbines is reconstructed using the methodology explained in section 1. The result is given in figure 12 and will be used to estimate fish damage rates in the next section.



		HPS	Sorn Castle	Quarry Bank Mill	Greenholme	Longbridge
Provided	Qmax	[m3/s]	1.25	1.85	9.85	13
	H	[m3/s]	2.2	3.9	4.1	2.3
	N	[rpm]	375*)	500	210	133
	D	[m]	0.65	0.7	1.6	2
	Dhub	[m]	0.26	0.27	0.64	0.8
	D_IGV	[m]	1.15	1.1	2.55	3.2
	H_IGV	[m]	0.33	0.288	0.68	0.86
	Dhub/D	[-]	0.40	0.39	0.40	0.40
	D_IGV/D	[-]	1.77	1.57	1.59	1.60
	H_IGV/D	[-]	0.51	0.41	0.43	0.43
	No. blades		4	4	4	4
	Regulation		fixed	variable	variable	variable
	No. GV		14	18	16	18
	GV regulation		variable	variable	variable	variable
	Max. GV angle	[degr]	50		55	60
Estimated	Qr (70% Qmax)	[m3/s]	0.88	1.30	6.90	9.10
	PHI	[-]	0.21	0.18	0.19	0.21
	PSI	[-]	0.26	0.23	0.26	0.23
	Ns	[-]	3.67	3.87	3.62	4.06
	Ds	[-]	1.52	1.48	1.53	1.44
	Drunner	[m]	0.66	0.68	1.60	2.00
	eff (rated)	[-]	0.87	0.86	0.87	0.86
	alpha (rated)	[degr]	37.5	44.4	41.4	46.1
	beta (rated)	[degr]	15.8	13.7	14.9	15.7
	alpha (max)	[degr]	47.6	54.4	51.6	56.0

Table 1: Data on four HP schemes provided by BHA and estimated values.
$^{*)}$ actual operating speed is 250 rpm



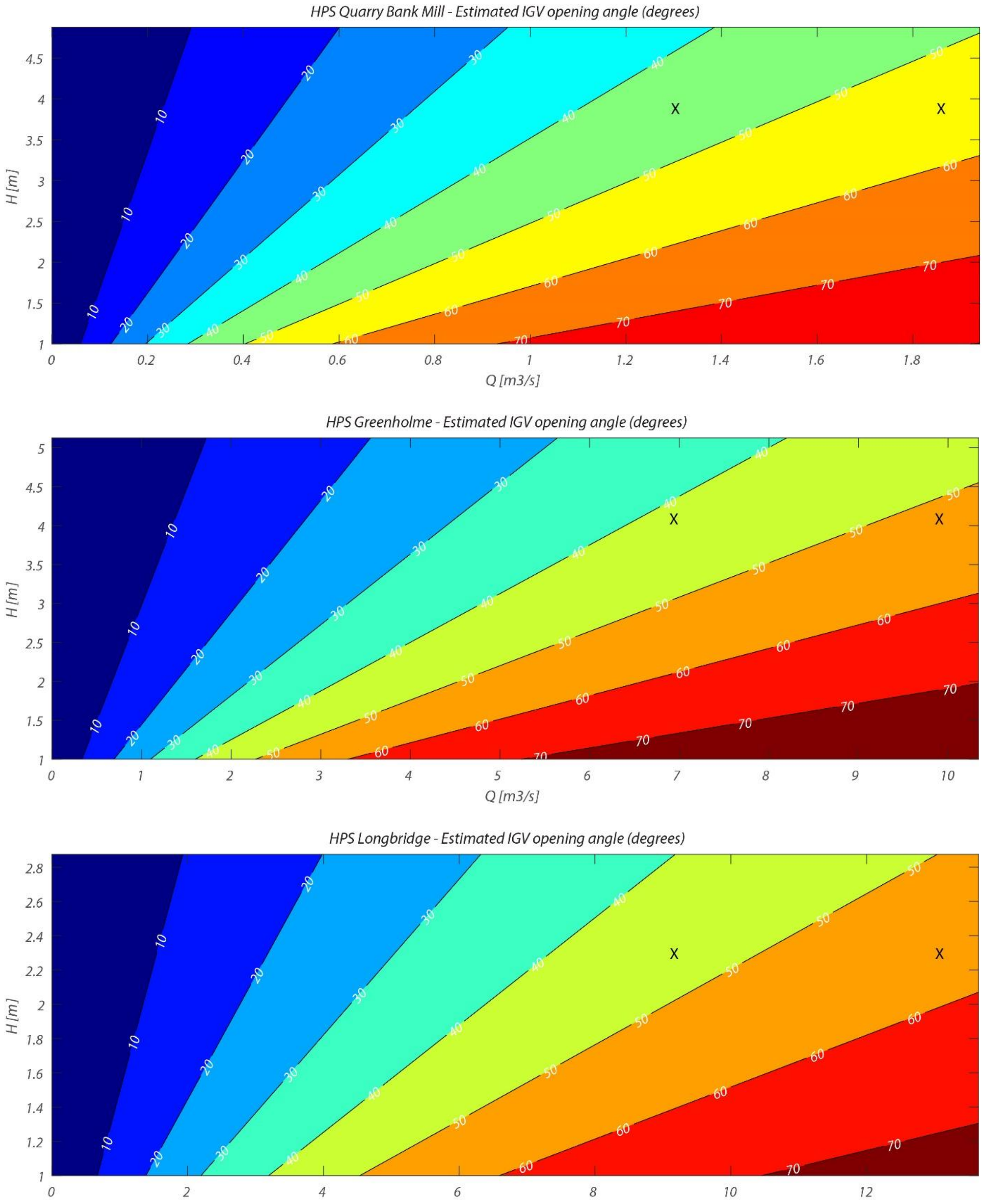


Figure 12: Estimated IGV control settings for HPS Sorne Castle, Quarry Bank Mill, Greenholme, and Longbridge. The rated operating condition and the maximum flow rate are indicated in the graphs (X).

3. FISH DAMAGE RATE ESTIMATIONS

Research on the mechanisms responsible for fish damage in pumps and turbines gained momentum after the start of the US Department of Energy's Advanced Hydropower Turbine Systems (AHTS) program in 1994. One of the goals of this program was to develop a new or improved runner for a hydropower turbine system that would reduce the risk of injury and mortality to fish passing through. An important step in the AHTS program was to study the biological criteria for fish injury and mortality. The laboratory experiments that were conducted were aimed at the three main mechanisms for damage to fish passing through turbine systems: mechanical damage, velocity shear, and pressure fluctuations (Cada et al., 1997).

Mechanical injury by blade strike is generally regarded as the primary cause of damage to fish passing through turbine systems with heads up to 30 m (Turnpenny et al., 2000; Cook et al, 2003; Amaral et al., 2011). It can lead to bruises, haemorrhage or even severing of the body.

Grinding of fish in the gaps between the adjustable runner blades and the stationary casing or hub, is also often mentioned as an important cause of mortality in turbines (e.g. Odeh, 1999). However, several studies that were done to assess the alleged positive effect of reduced gaps did not arrive at a unanimous judgment (Cada, 2001; Cada and Amaral, 2011; Deng et al., 2011). Because of this, mortality caused by the gaps is not considered in this study. It should be stressed, however, that their importance cannot be ruled out.

This study follows the Dutch standard NEN 8775 "Fish safety – Method for determining the fish safety of pumps, Archimedean screws and pressure turbines used in pumping stations and hydroelectric plants". A blade strike model calculates the theoretical probability of a collision between the runner blades and a fish of a given length. This probability is then multiplied by the mutilation ratio, which is the probability that a blade hit (of a given velocity) will lead to instant death or lethal injury. The result of this is the damage probability for a fish passing through the turbine.

A correlation by Van Esch (2012) of the most recent measurements of blade strike mortality rate by EPRI (2008/2011) is used in NEN 8775 to calculate the mutilation ratio of a blade strike for salmon smolts. For eel, a correlation by Van Esch (2014) is used, based on measurements with European eel of 40-60 cm. These models correlate the blade strike mortality ratio with the velocity at impact and the ratio of fish length to leading edge blade thickness.

The following assumptions are made:

- *blade thickness is 1% of the runner diameter*
- *fish move passively with the flow*
- *fish enter the turbine distributed uniformly over the entrance area*
- *small eel (<40 cm) suffer mutilation rates in accordance with the NEN norm, even though their physiology may be quite different from larger eel*

The mortality rate depends on the length of the fish, its species, the opening angle of the IGV, the flow rate, and the shaft speed of the runner. This means that probabilities of mortality can be displayed in Hill-graphs, as a function of head and flow rate.

Fish damage estimations for the four BHA hydropower schemes are given figs. 13-16 in the next sections.

3.1 SORNE CASTLE

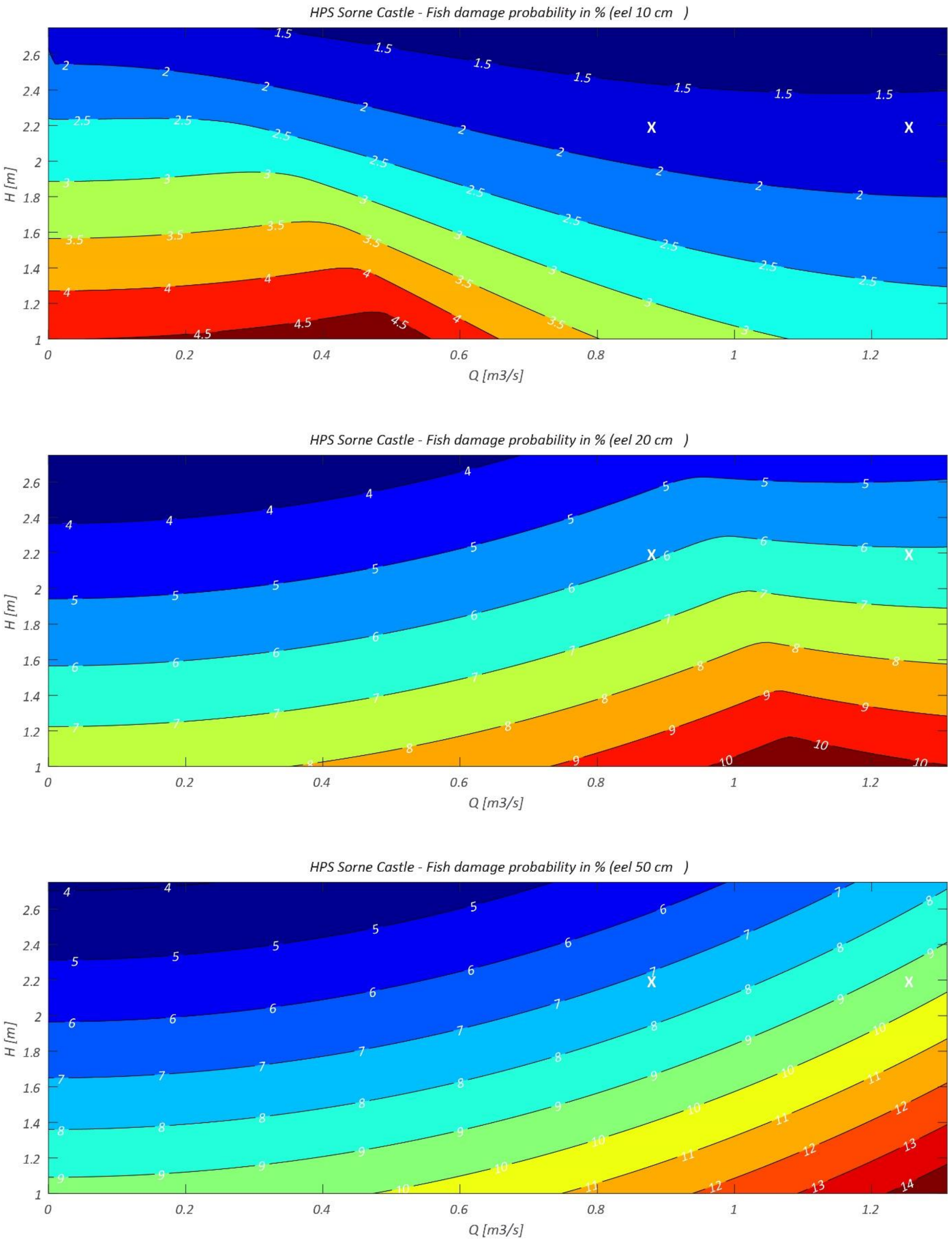
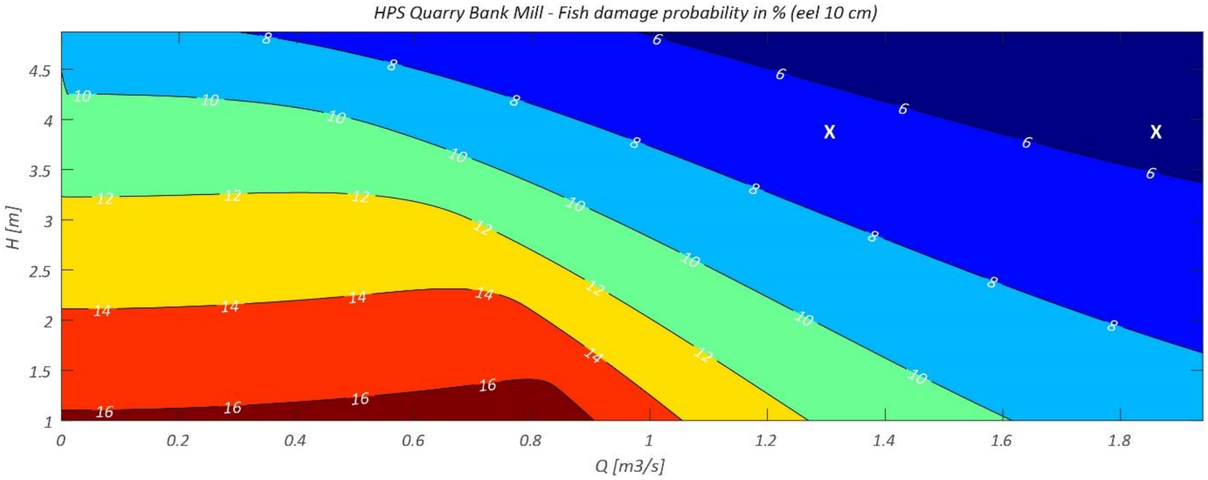
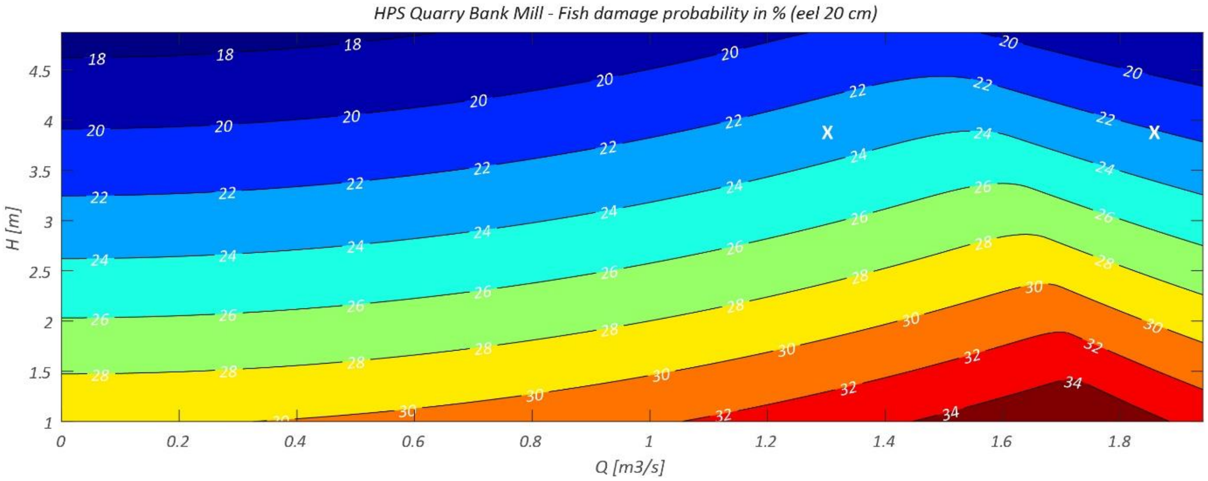


Figure 13: Damage rates to eel at HPS Sorne Castle (D_{runner} = 0.65 m, N = 375 rpm). The rated operating condition and the maximum flow rate are indicated by X.

3.2 QUARRY BANK MILL





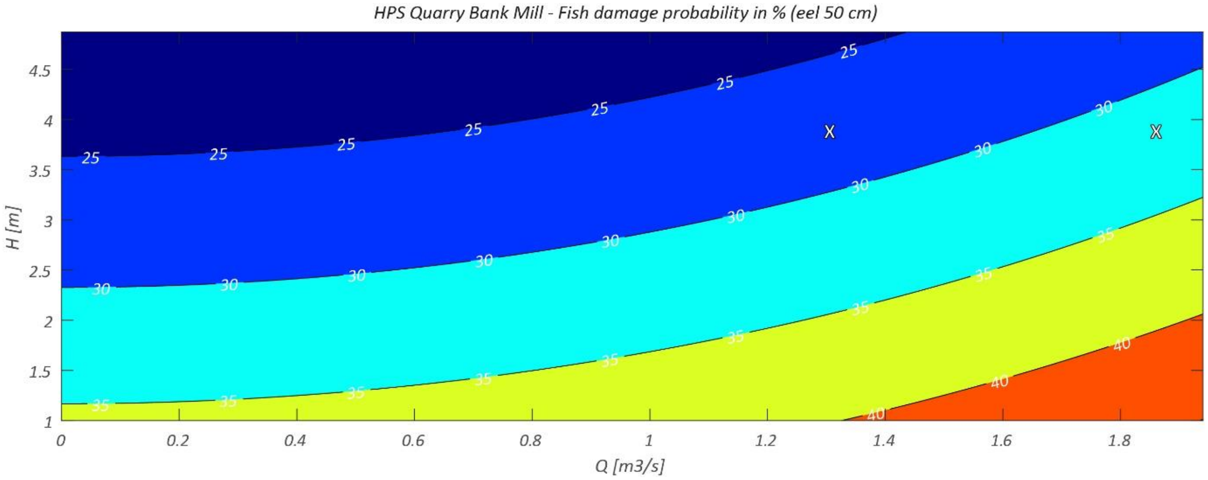


Figure 14: Damage rates to eel at HPS Quarry Bank Mill (D_{runner} = 0.7 m, N = 500 rpm). The rated operating condition and the maximum flow rate are indicated by X.

3.3 GREENHOLME

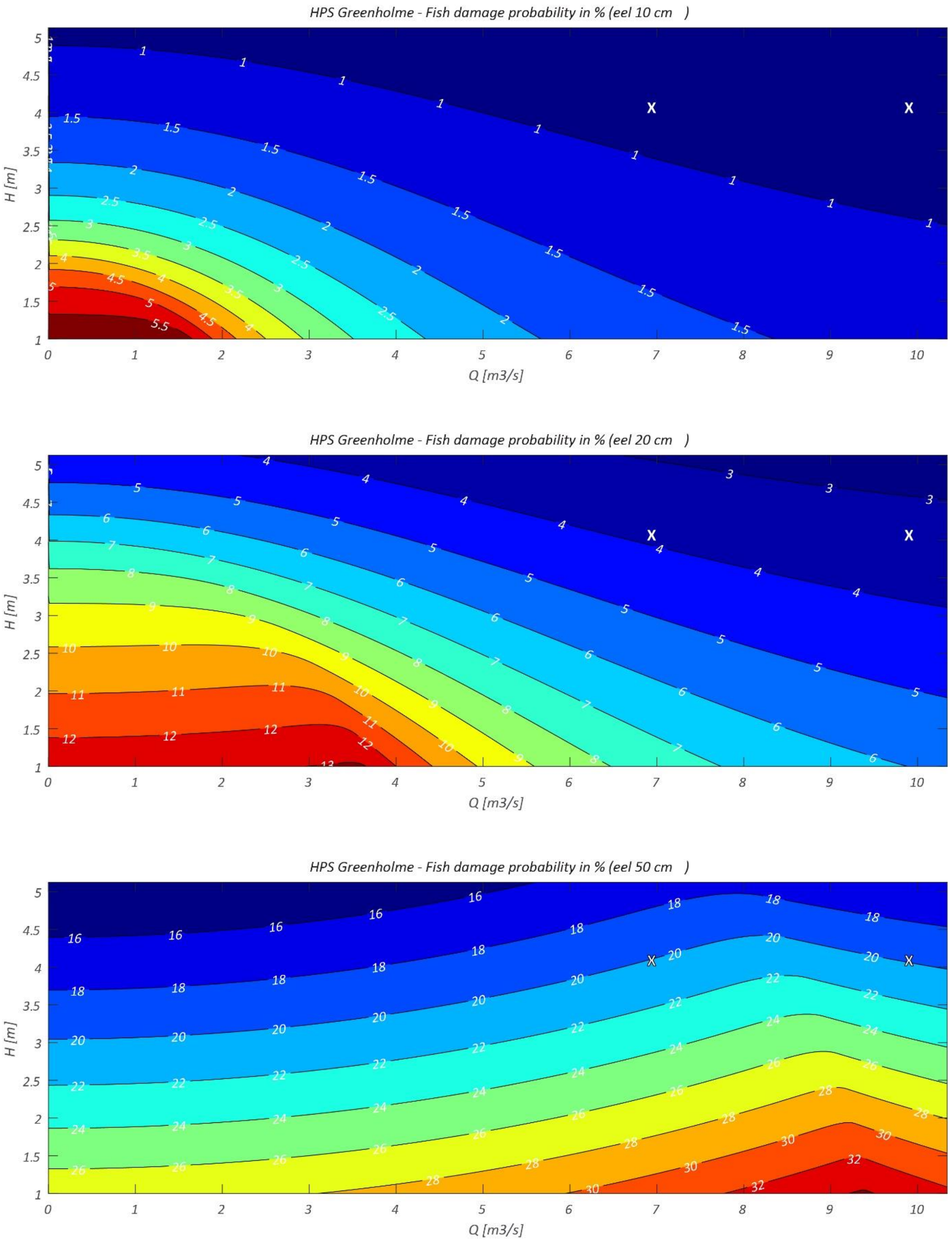


Figure 15: Damage rates to eel at HPS Greenholme (D_{runner} = 1.60 m, N = 210 rpm). The rated operating condition and the maximum flow rate are indicated by X.

3.4 LONGBRIDGE

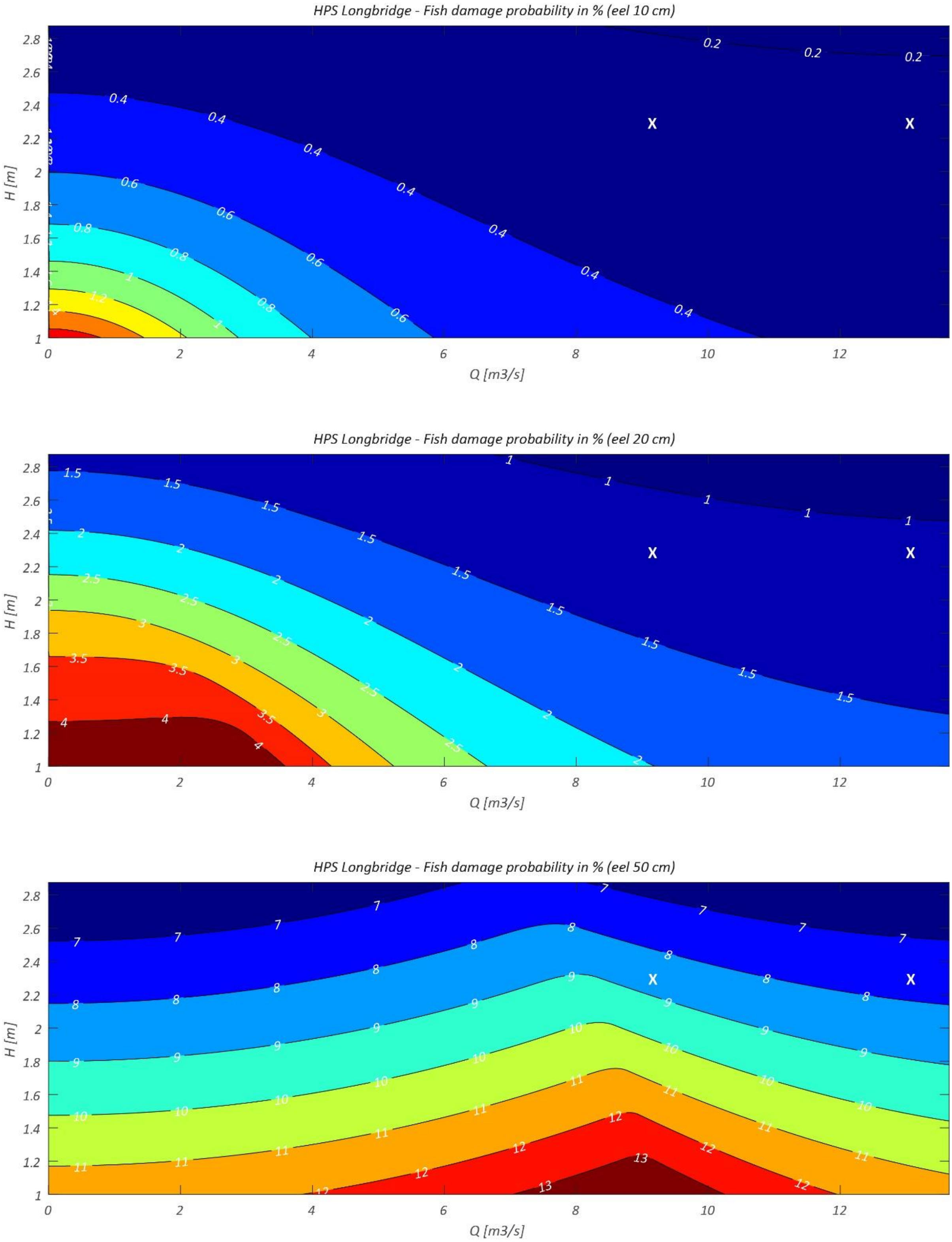


Figure 16: Damage rates to eel at HPS Longbridge (D_{runner} = 2.00 m, N = 133 rpm). The rated operating condition and the maximum flow rate are indicated by X.

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Longbridge Hydro

Abstraction License Variation - Supporting Evidence

14th March 2022

Part B

B11.1 the site is existing, there is no planning requirement for the proposed changes to the site.

B17 Please see below map (attached to the existing licence) showing abstraction and discharge locations, there are no proposed changes to these.

Part C

1. The application fee

   It is proposed to pay the fee by Credit Card, Please contact; Paul Jardine at the details given in section A8.1 for payment.

2. Details of how you calculated the amount of water you intend to abstract.

   This application is for the variation of an existing licence;

   Section C3, no proposed change to existing licence
   Section C4, no proposed change to existing licence
   Section C5, no proposed change to existing licence

3. Confirmation of the right of access or negotiations so far;

   Existing Site, access and ownership are already in place. Please refer to attachment titled "Longbridge land Ownership Map" which identifies in RED those areas owned as freehold titles by Derby City Council. The map identifies Asset Code 00956, which is the site of the hydroelectric generation plant.

4. Details of aggregation with existing licences; N/A

5. Environmental statement or report; N/A

6. Evidence of discussion with fisheries department re Eels (England & Wales) Regulations;

   Preliminary discussion not yet undertaken, contact was attempted with Matt Buck, but unsuccessful due to annual leave absence.

   A preliminary discussion was held with Damian Mason regarding this application.

   The aim of the proposed works is to increase the renewable energy generation of the site. The site has, and is underperforming due to screen and screen cleaning issues, part of which is due to the large amount of gravel and stones which block the existing screen. It is estimated that the additional energy capture could be as much as 300,000 kWhrs/annum.

   There is evidence contained within a report that Longbridge hydroelectric generation site causes minimal damage to fish (eel).

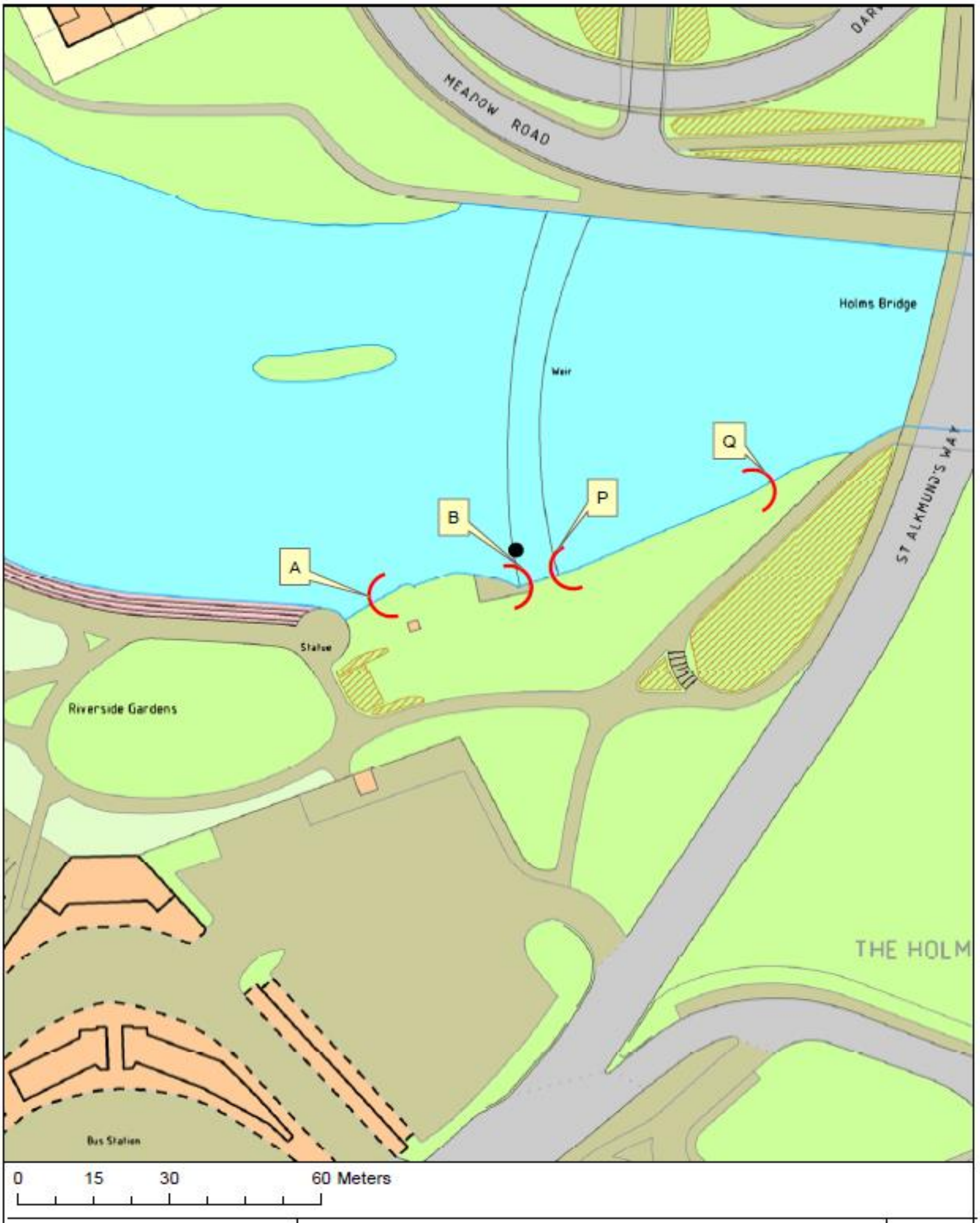
The report – attached to this application - provides data in graphical format for the percentage probability of damage to eel. This is sub divided into three separate size groups; 10cm, 20cm and 50cm for the four site examined by the report. At the Longbridge site, for the 10cm and 20cm groups the fish damage probability is <0.3% and <1.3% respectively.

Given that the screening installed at Longbridge is angled across the flow directing fish towards the large fish by-wash it is expected that the actual percentage for the probability of fish damage would actually be less than theoretically modelled. In addition to this, due to the turbulent nature of the flow through the screen and turbine it is suggested that the fish would naturally be attracted to the steady state flow through the fish by-wash rather than the chaotic nature of the water passing through the screen.

An increase of the spacing of the bars as proposed from 12.5mm to 25mm results in an overall increase in ‘open area’ of the screen of only 8.19% in part due to a related increase in bar thickness (6mm to 8mm, to improve the inherent strength in the screen). The increased spacing of the bars would also decrease the water velocity through the screen by a calculated 10%.

Please refer to attached report ‘Damage to Fish in Kaplan-Type Hydro Turbines’ Dated 05-02-2021 written by Dr B.P.M. van Esch. One of the turbines specifically referenced within this report is; HPS Longbridge.

Map identifying abstraction and discharge locations as detailed within Licence Ref: 3/28/48/42/S



ENVIRONMENT AGENCY

MAP ACCOMPANYING LICENCE NUMBER
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