FISHTEK
CONSULTING

Archimedean Screw risk assessment:
strike and delay probabilities

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Clients: Ham Hydro CIC, Spaans Babcock, Ritz Atro, B.Spoke℮Waterpower

1. Introduction

There has been a large resurgence of interest in hydropower in the UK recently, due principally to the introduction of the Feed In Tariffs (FITs), which have made hydropower a significantly more economically viable method of generating electricity.

One of the recent additions to the range of hydroturbines typically installed at sites in the UK has been the Archimedean screw turbine. The first such system was installed at the River Dart Country Park in 2007 and since then a large number of Archimedean screws have been installed across the UK. They are increasingly becoming the preferred hydro-turbine for low-head site developments across the UK, due to a large degree to their so-called ‘fish-friendly’ nature.

1.1 Fish trials through Archimedean screws

Fish passage trials performed on Archimedean screws have shown that no significant damage is caused to fish that enter and pass through these turbines. In the UK, this has been demonstrated for salmonids naturally passing down an Archimedean screw and artificially introduced (Kibel, 2007; Kibel and Coe, 2008), eels (Kibel and Coe, 2008), coarse fish (Kibel, Coe and Pike, 2009) and lampreys (Lucas and Bracken, 2010).

In addition, studies performed in other countries have shown that Archimedean screws do not cause serious damage to fish passing through them (Spah, 2001; Vis Advies, 2007).

The first assessment of fish passage through Archimedes turbines was conducted by Spah (2001). The turbine tested had a diameter of 1.4 m and processed 615 litres of water per second. 158 fish of nine species were passed through the turbine and netted at the outflow. 4.4% of the fish suffered limited damage, mainly scale loss that was deemed to be minor and generally recoverable. Chub and roach were the only species to suffer any damage; eels that traditionally experience problems passing through turbines suffered no damage at all. Table 1 summarises the results.

Table 1: Summary of results from Spah (2001), showing the number that passed through of each species and the lengths of fish affected

Species	No. Tested	Length Range (cm)	No. fish Injured	Injuries
Eel	22	36-58	0	
Grayling	3	20-36	0	
Brown trout	31	8-35	0	
Perch	19	14-18	0	
Chub	63	8-43	5	Scale loss, haematoma
Gudgeon	8	12-14	0	
Bullhead	3	11-14	0	
Dace	1	21	0	
Roach	8	16-21	2	Scale loss, haematoma

The conclusions of the report were that the damage was most likely due to the leading edge becoming sharpened by stones after prolonged operation. The study conducted by Vis Advies (2007), netted fish naturally passing through an Archimedean screw at Hooidonkse Mill on the River Dommel in Holland. A total of 289 fish, mainly small bream passed through the screw.

None of the fish suffered any damage at all. This was verified by the project leader, Tim Vriese (pers. comm.) who confirmed that each fish was carefully checked for any signs of damage including limited scale loss, but none was found. Results of the river Dommel study are shown in table 1A.

A number of studies by Fishtek Consulting (Kibel et al, 2007, 2008, 2009) at the River Dart in Devon and at Howsham Mill on the River Derwent, concluded that with appropriate mitigation, the risk of injury to fish from passage through an Archimedes was very low indeed. Results of these studies are summarized in table 2.

Table 1A: River Dommel study. Size range and number of each species

Species	**Size range (cm)**	**Number**	**Number of fish with damage**
Bitterling	4-5	5	0
Bleak	4-5	2	0
Bream	3-7	239	0
Carp	7-19	11	0
Crucian Carp	9-14	2	0
Gudgeon	11	1	0
Orfe	8-14	2	0
Pike	39	1	0
Roach	5-12	9	0
Rudd	4-11	2	0
Stickleback	1-5	5	0
Stone Loach	11-11	3	0
Tench	4-20	7	0

Although over 100 screw turbine systems are currently operational on the continent, with no reported fisheries issues or problems, in the UK recommendations are in place to reduce the risk of injury from Archimedean screws even further. Work by Fishtek Consulting on the risk of injury should a fish be struck by the leading edge of a turbine led to the recommendation that in order to minimise the risk of injury, the leading edges of small Archimedean screws under 2.5 m diameter should be fitted with rubber bumpers and larger turbines with compressible bumpers that reduce the force to which fish are subjected following contact to well within the damage threshold (Kibel, Coe and Pike, 2009).

Table 2: summary of results for 1500 fish passages from R. Dart and Howsham Mill Monitoring

Fish Species	Maximum Length (cm)	Damage Sustained
Barbel *(Barbus barbus*)	61	None
Bullhead *(Cottus cottus*)	14	None
Brown trout (*Salmo trutta*)	44	None
Chub (*Leuciscus cepahalus*)	48	None
Eel (*Angiulla angiulla*)	79	Pinched tail (0.64%)
Grayling (*Thymallus thymallus*)	28	None
Gudgeon (*Gobio gobio*)	15	None
Perch (*Perca fluviatilis*)	30	None
Pike (*Esox lucius*)	77	None
River lamprey (*Lampetra fluviatilis*)	32	None
Roach (*Rutilis rutilis*)	22	None
Salmon smolt (*Salmo salar*)	17	4 fish out of 280 (1.4%) with minor scale loss – recoverable
Salmon Kelt (*SalmoSalar*)	98	None
Sea Trout (*Salmo trutta*)	58	None

1.2 Basic hydraulics of Archimedean screws

Archimedean screws work on a relatively simple principle whereby water passes down a long screw, set at an angle of approximately 22 degrees, the gravitational of which causes the screw to turn, generating energy, which is then converted to electricity (see figure 1).

There are four factors that influence the volume of water that can pass down an Archimedean screw and the energy generated. The manner in which each of these variables has an effect is as follows:

1. *Diameter*: all other factors being equal, the larger the screw, the larger the volume of water that it can pass and the greater the quantity of energy that it can generate
2. *Rotational speed*: all other factors being equal, a screw turning at a higher rpm will have a larger volume of water passing through it (per unit time) and will generate a higher quantity of energy
3. *Number of blades*: all other factors being equal, a screw with more blades can handle a greater volume of water and will generate a higher quantity of energy
4. *Pitch*: this is the axial spacing between the blades on the screw and is equal to the diameter of the screw divided by the number of blades.

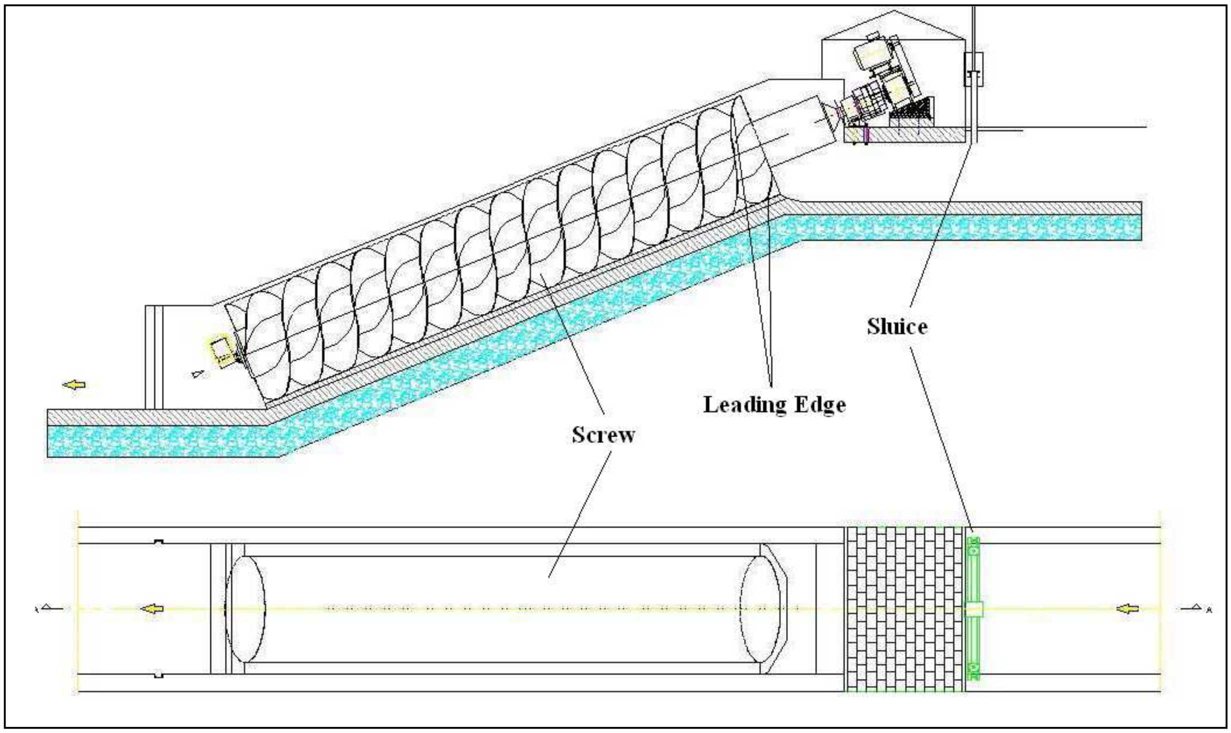

Figure 1: diagram of an Archimedean screw turbine in both elevation and plan view

The systems currently working within the UK (as of March 2011) are all 3-bladed systems, however there are schemes being proposed and licensed for the installation of 4-bladed systems.

1.3 Report aims and objectives

While the previous work on Archimedean screws has demonstrated that no significant damage is caused to fish passing through the systems tested, there are concerns being raised about the possible effect on fish of systems of different sizes and with a higher number of blades on fish. Increasingly, proposals include designs for 4 and 5 bladed turbines as they can process more water for a given diameter.

The concerns are being raised by both fisheries specialists within the Environment Agency and angling organisations and can be split into several specific issues, as follows:

1. For screw systems with a higher number of blades there is a higher chance of fish contacting a leading edge. This problem is compounded by the use of smaller screws, which have higher rotational speeds. If this does, as predicted, lead to an increase in the proportion of fish that contact a leading edge, how much of an increase will occur?
2. If more fish contact a leading edge on a screw as they pass into the screw, does this matter? What is the chance of injury occurring?
3. Downstream migration is an important component of the life history and ecology of many fish species. Previous work has demonstrated that fish of several species naturally pass down through Archimedean screws. However it is not known if smaller screws and screws with more blades deter fish from entering and passing downstream. If this is predicted to occur, is it possible to say to what extent?

This report will address each of these issues using a combination of theoretical predictions, reference to published literature and empirical observations of the behaviour and interactions between fish and Archimedean screws. For each of the specific issues, if the expansion in the range of screws being proposed for installation around the UK is likely to cause a problem, suitable mitigation and legislative measures have been suggested.

2. Probability analysis of leading edge contact

2.1 The design of Archimedean screws

The variables that are altered to control the flow through and power output of Archimedean screws are described in section 1.2. There is a direct relationship between size and rated rpm for Archimedean screws with smaller machines having a higher average rpm. This relationship is shown for a range of commercially available 3-bladed systems in figure 2 (data obtained from Rehart, Ritz Atro and Spaans Babcock) and is a result of the optimisation of the flow rate and rpm for screws of different sizes.

As mentioned previously, one of the principle concerns behind this report is the introduction to the UK of 4- and 5-blade screw systems. The first few machines installed in the UK were all 3-blade screws. The relationship shown in figure 2 is extended in figure 3 to include systems with 4 and 5 blades. This is a total of 201 different screw systems (data obtained from manufacturers), of different sizes and blade numbers. From this figure it is clear that 3-blade screws cover a wider range of sizes (and hence rpm) than 4- and 5-blade screws.

It is also important to note that there are practical operational limitations on the interaction between screw size and the number of blades. The data shown in figure 2 is a plot of the size and rpm of 3, 4 and 5-blade screws that are actually manufactured. Note that 5-blade screws are not made in the very small sizes of 3-blade or 4-blade screws. The only 5-blade screws being made currently are large systems, > 2 m in diameter.

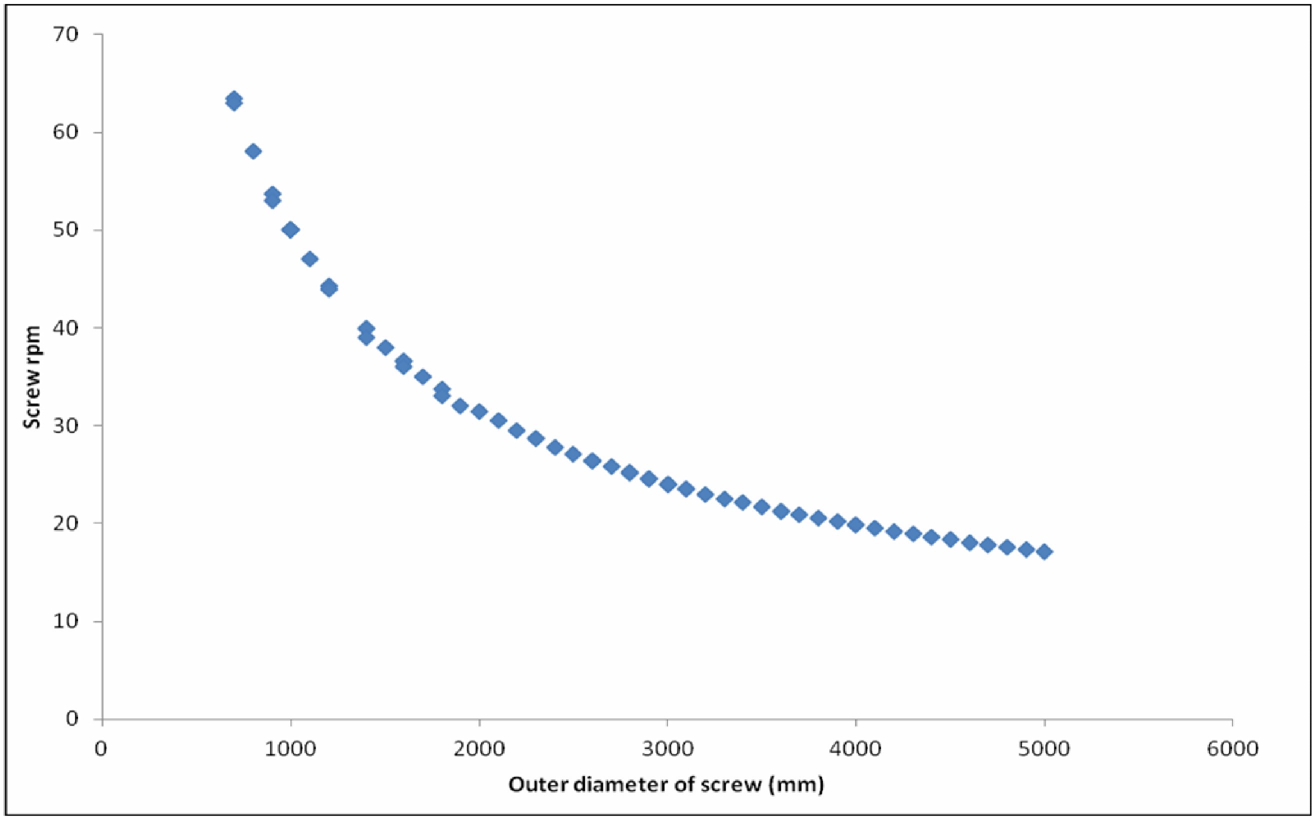

Figure 2: relationship between screw diameter and rotational speed (rpm) for a range of commercially available 3-blade Archimedean screw turbines

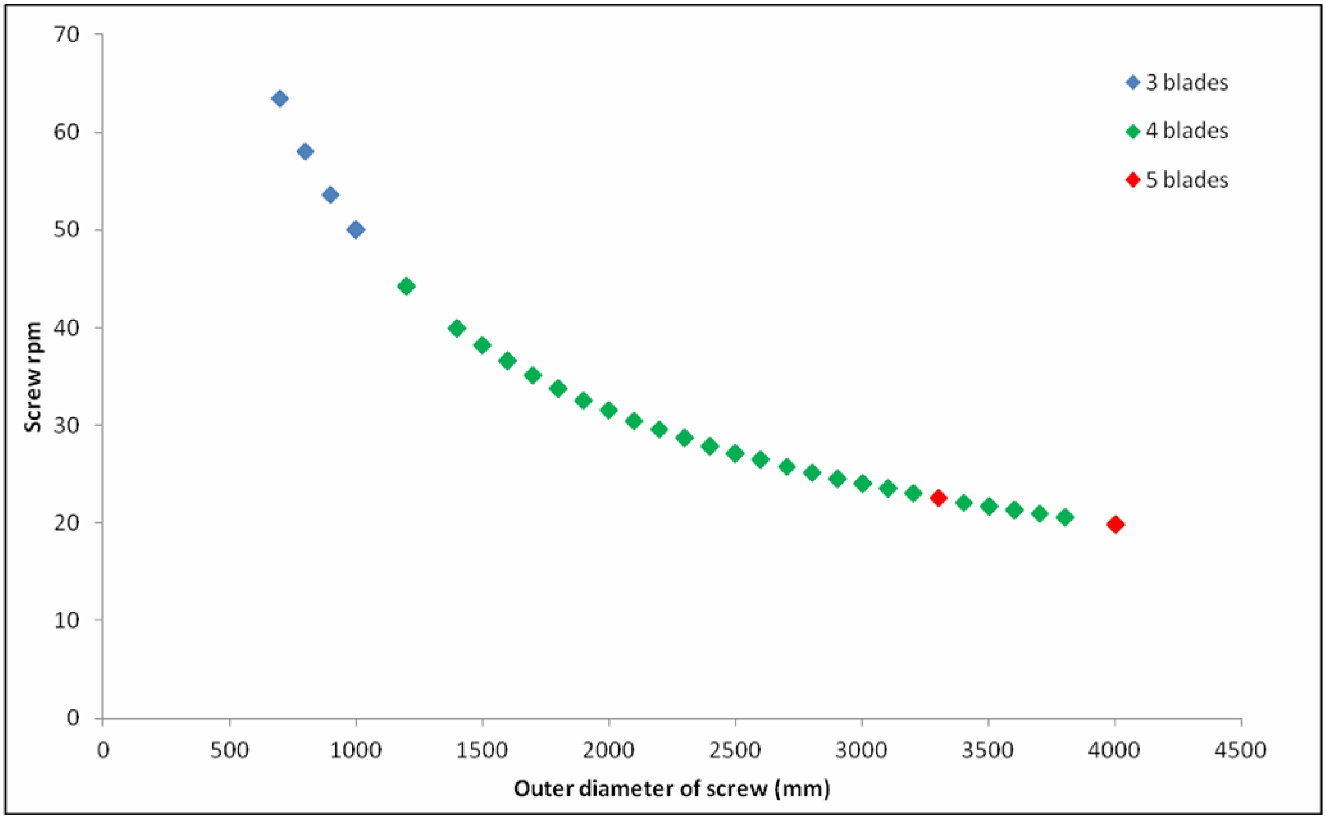

Figure 3: relationship between screw diameter and rotational speed (rpm) for a range of commercially available 3-, 4- and 5-blade Archimedean screw turbine

The only point at which a fish can be contacted by the screw blades is as it crosses the leading edge of the helix. These leading edges are the upstream end of each of the helices that form the screw and are shown in figure 4. As the screw turns, the leading edges scribe a continuous circle at the entrance to the screw, across which fish must pass when they enter the first chamber.

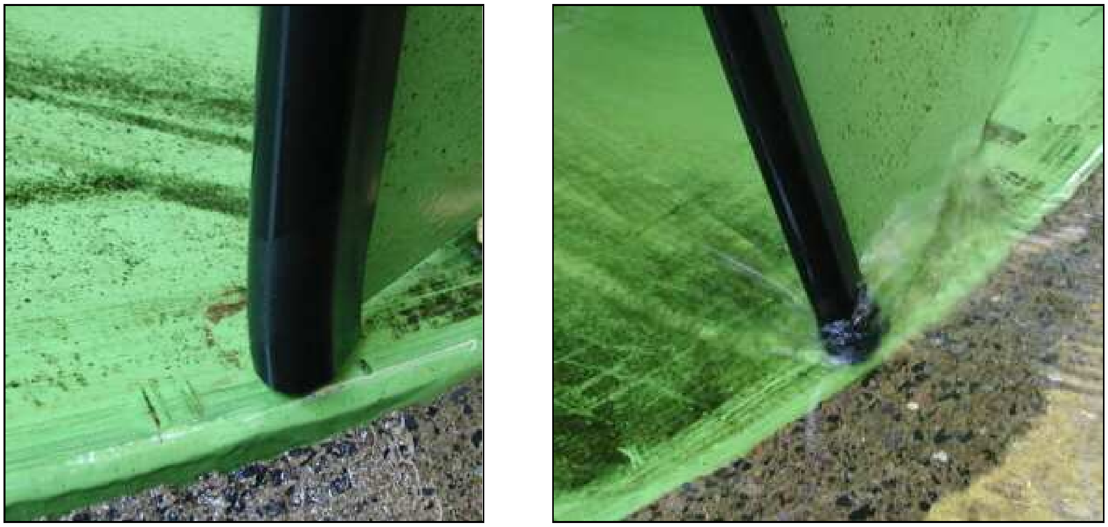

Figure 4: images of the leading edge of a screw, fitted with a rubber bumper

It is obvious that for a screw of a certain size and rpm, the chance of a fish contacting a leading edge is higher for a system with more blades. Equally, a screw turning at a higher rotational speed has a greater chance of contacting a fish with a leading edge. In both cases, a greater number of blades or higher rpm reduces the time between leading edges passing a given point on the circles scribed by the leading edges (see figure 5).

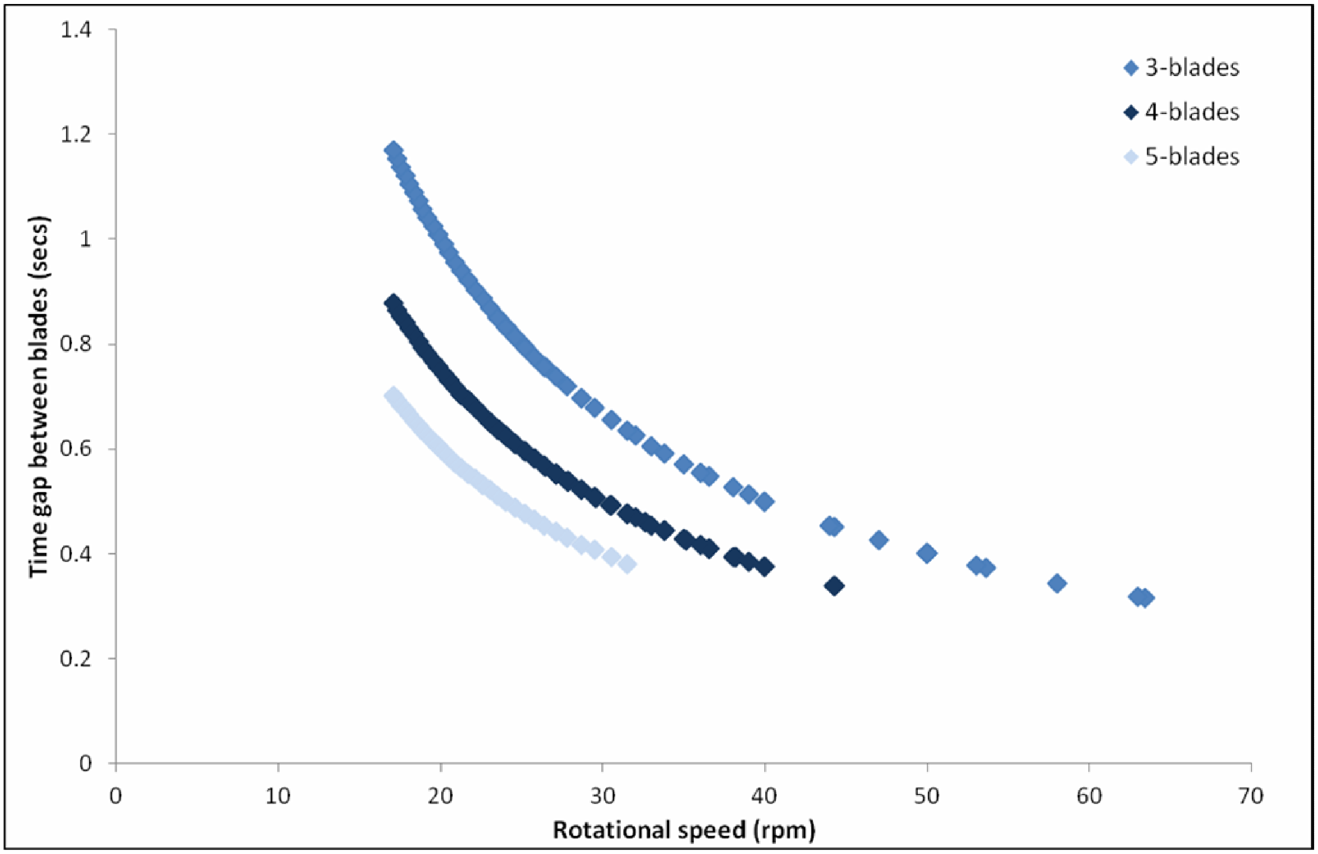

Figure 5: time gap between blades for screws with differing rotational speeds and numbers of blades

2.2 Probability model development

From a purely mechanistic perspective (ignoring for example any behavioural responses of fish to avoid the leading edge of the screw), the probability of a fish contacting one of the leading edges of the screw as it enters is a result of the interplay between various parameters, principally the following:

1. *The speed at which the fish enters the screw*

The speed at which a fish enters the screw is a direct result of the velocity of the water entering the screw. Trials at the River Dart Country Park (Kibel, 2007), in which a large number of fish were observed showed that fish typically dropped back into the screw under neutral forward velocity, entering the screw at a speed equal to the velocity of the water entering the screw. (It should be noted that as the flow of water into a fixed speed Archimedean screw reduces, the depth of water reduces, while the velocity of water entering the screw remains approximately the same).

2. *The size (length) of the fish*

A wide variety of fish have been recorded passing down Archimedean screw turbines (Kibel, 2007; Kibel and Coe, 2007; Spah, 2001; Vis Advies, 2007). Due to their increased length, larger fish will take longer to pass the leading edge of the screw.

3. *The position at which the fish enters the screw, relative to the leading edge*

This refers to the position that a fish enters in the space between the leading edge of the blades. For example, in figure 6 a fish crossing the leading edge circle at point X_1 will have a greater amount of time to cross the leading edge than a fish crossing the leading edge circle at point X_2 as it is further ahead of the approaching leading edge.

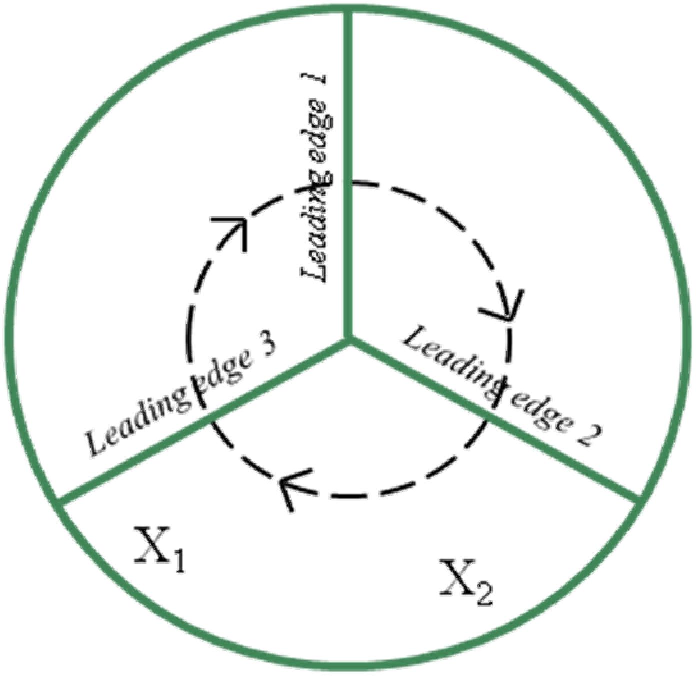

Figure 6: diagrammatic representation of the leading edge of an Archimedean screw and example positions at which two fish could enter the screw

4. *The speed of the screw (in rpm)*

As seen previously, the design speeds of screws is largely dependent on the size of the screw, larger screws having slower rotational speeds

5. *The number of blades on the screw*

The greater the number of blades that a screw has, the greater the number of leading edges that could potentially contact a fish passing into the screw.

It is possible to integrate these different parameters into a model that predicts the probability that a fish passing across the leading edge will be struck. For an individual fish this probability (*P*) has a bimodal form; fish either contact a leading edge of the screw or they do not. The model can be described as follows:

$$T_S \text{ (seconds)} = (60/Un).(\lambda/\Lambda)$$

$$T_F \text{ (seconds)} = L/V$$

P is conditional, such that: If $T_S > T_F$, $P = 0$ *(fish does not contact leading edge)*
If $T_F > T_S$, $P = 1$ *(fish contacts leading edge)*

Where:

U *= rotational speed of screw (rpm)*

n *= number of blades in screw*

λ *= the angle (in degrees) formed by the point at which the fish enters the screw and the next leading edge (see figure 7)*

Λ *= the angle (in degrees) between leading edges. For 3-bladed screws this is* 120^{o}*, for 4-bladed screws this is* 90^{o} *and for 5-bladed screws this is* 72^{o}

V *= the velocity of the water entering the screw (m/s)*

L *= the length of the fish (m)*

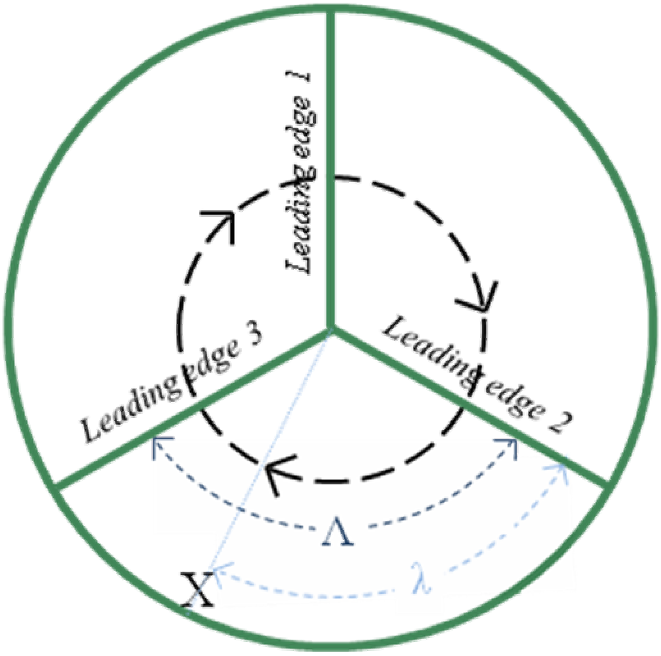

Figure 7: illustrative diagram showing λ and Λ, as described in the model. 'X' is the position at which the fish crosses the circle scribed by the leading edges of the screw

The model has an underlying principle that is very similar to that of the STRIKER model of Turnpenny *et al.* (2000), in which the probability of a fish contacting a leading edge is related to the ratio of 'fish length' to 'water length'. In order for a fish to pass into the screw on any given streamline without contacting a leading edge, it must pass after the sweep of one blade and before the sweep of the next. In the model described here, the two 'lengths' are temporal and are essentially the length of time it takes for a fish to cross the leading edge circle and the length of time before the next blade passes.

However, unlike the STRIKER model, which was developed for kaplan turbines, the model described above does not include the actual velocity of the blades as a factor. The only variables of the screw within the model are the rotational speed and the number of blades that the screw has. These two factors alone describe the *temporal* space between two leading edges (which in turn dictates the probability of a fish being struck) and are independent of the size of the screw (although the rpm of a screw is directly related to its size (see figure 2). As such, the STRIKER model is not appropriate for assessing injury risk in Archimedean screws.

2.3 Modelled probability of leading edge contact

For an individual fish the probability that it will contact a leading edge is determined by the model described in section 2.2. For an individual fish, while this outcome is essentially bimodal, for a large number/population of fish passing through an Archimedean screw the individual events produce an overall proportion of fish that, for a given turbine rpm and blade number, will be predicted to contact the leading edge.

The model was therefore used to generate the proportion of fish of a given length that would be expected to contact a leading edge if fish were essentially behaving as inanimate objects entering the turbine at random positions between the blades (i.e. random values of λ).

These proportions were generated by running the model for 10,000 iterations for each of the supplied information for turbine systems that are currently commercially available (a total of 201 systems), for fish of a certain length (from 0.1 to 1.0 m, at 0.10 m intervals), entering the turbine at random positions between the leading edge.

The result of these runs of the model were that the proportion of fish of a given size expected to contact a leading edge was determined for each of the 201 systems. The results are presented in figures 8-10. Note that approach velocity is also an important factor within the model and this depends on the size of the screw and the volume of water passing down the screw. This information is commercially sensitive, so is not presented specifically on the graph, but was included in the runs of the model, in the manner described in section 2.2.

The graphs show that for a given screw rotational speed, the probability of a fish contacting the leading edge increases for larger fish. Equally, higher screw rotational speeds have a higher probability of a fish of a given size contacting the leading edge. As smaller screws have higher rotational speeds, this therefore equates to an increased probability of fish contacting the leading edge in smaller screws.

The lines of best fit given show that the probabilities tend towards 1 (i.e. every fish passing through the screw will contact the leading edge) as the size of fish and rotational speed of the screw increase. The slope of the line for fish of a given size tends to be steeper for a screw with more blades. However, more of the lines tend to 1 for screws with 3 blades, as 3-bladed screws are made to smaller sizes than 4 and 5-bladed screws, with correspondingly higher rotational speeds. This factor indicates the over-riding influence that screw rotational speed has on the probability of a fish contacting the leading edge.

It should also be noted that, for a given rotational speed, a screw with more blades will not necessarily result in a higher probability of leading edge contact occurring. This is because, for a screw of a given size, an increase in the number of blades results in an increase in the volume of water that a screw can handle, with a subsequent increase in the approach velocity. This has the effect of compensating for the increased number of blades as the more quickly a fish passes the leading edges, the lower the probability that contact between the fish and leading edge will occur.

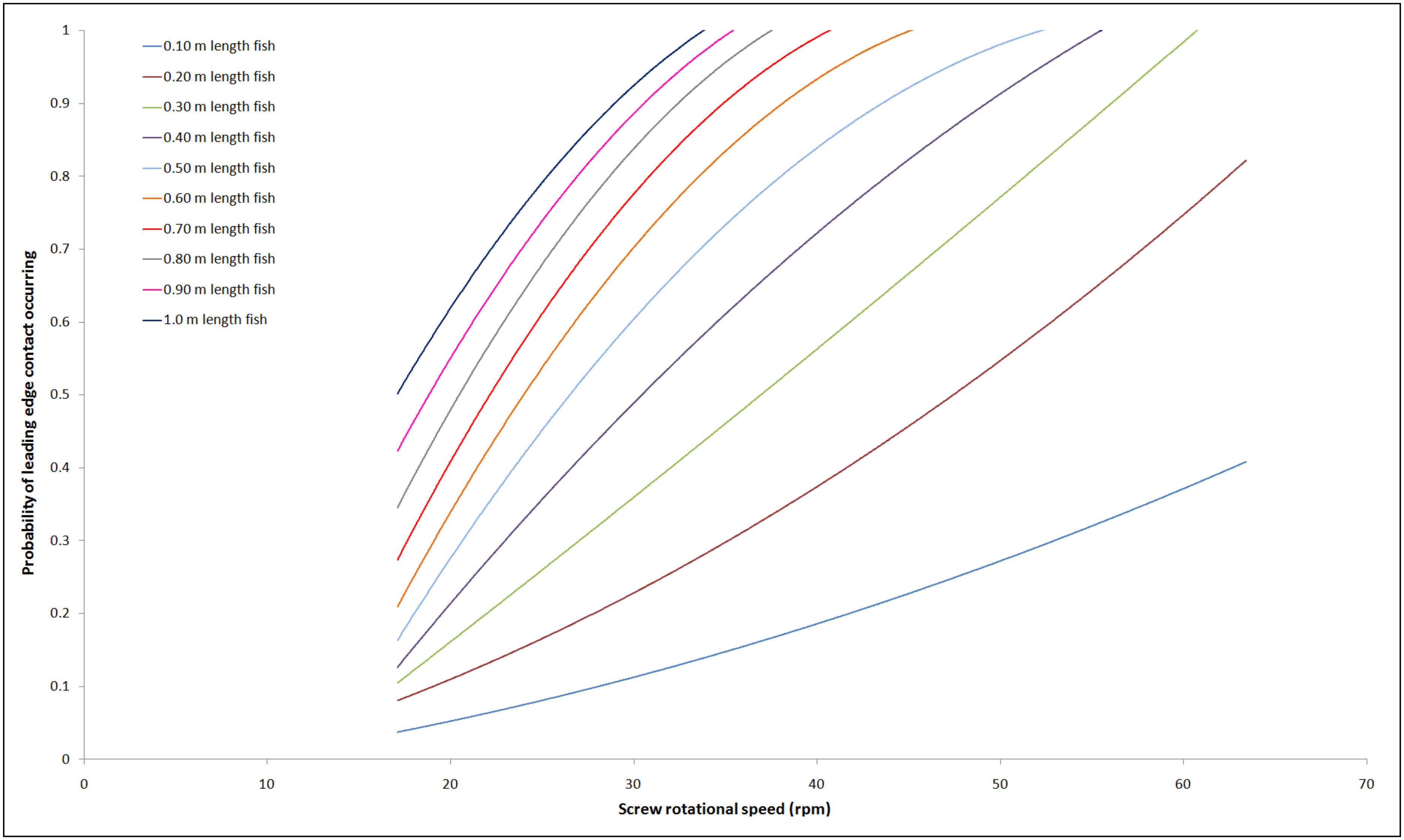

Figure 8: probability of leading edge contact for fish of different sizes passing through screw systems with different rotational speeds and 3 blades. Lines given are second order polynomial best fit lines to the raw data of 70 commercially available screw systems with 3 blades

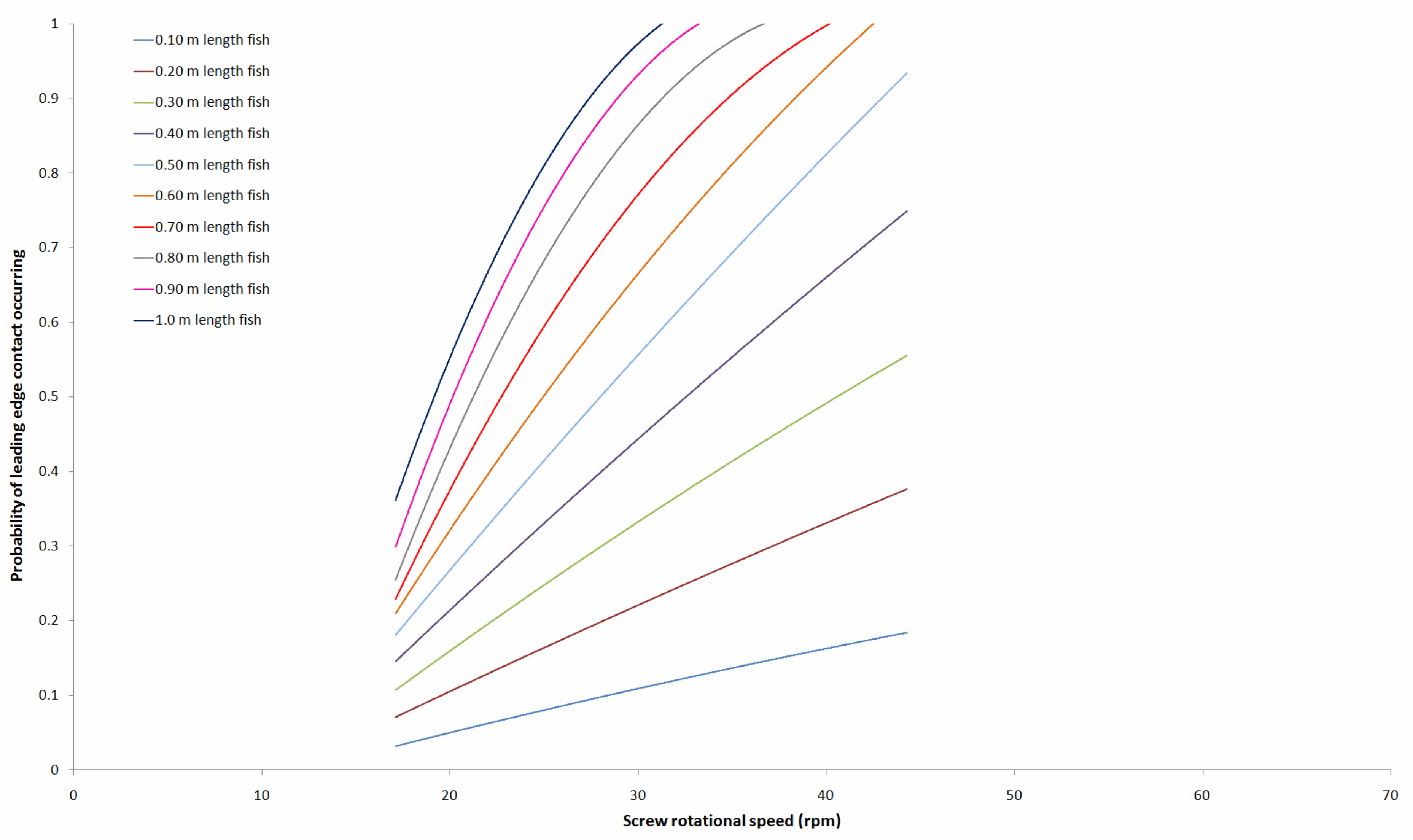

Figure 9: probability of leading edge contact for fish of different sizes passing through screw systems with different rotational speeds and 4 blades. Lines given are second order polynomial best fit lines to the raw data of 98 commercially available screw systems with 4 blades

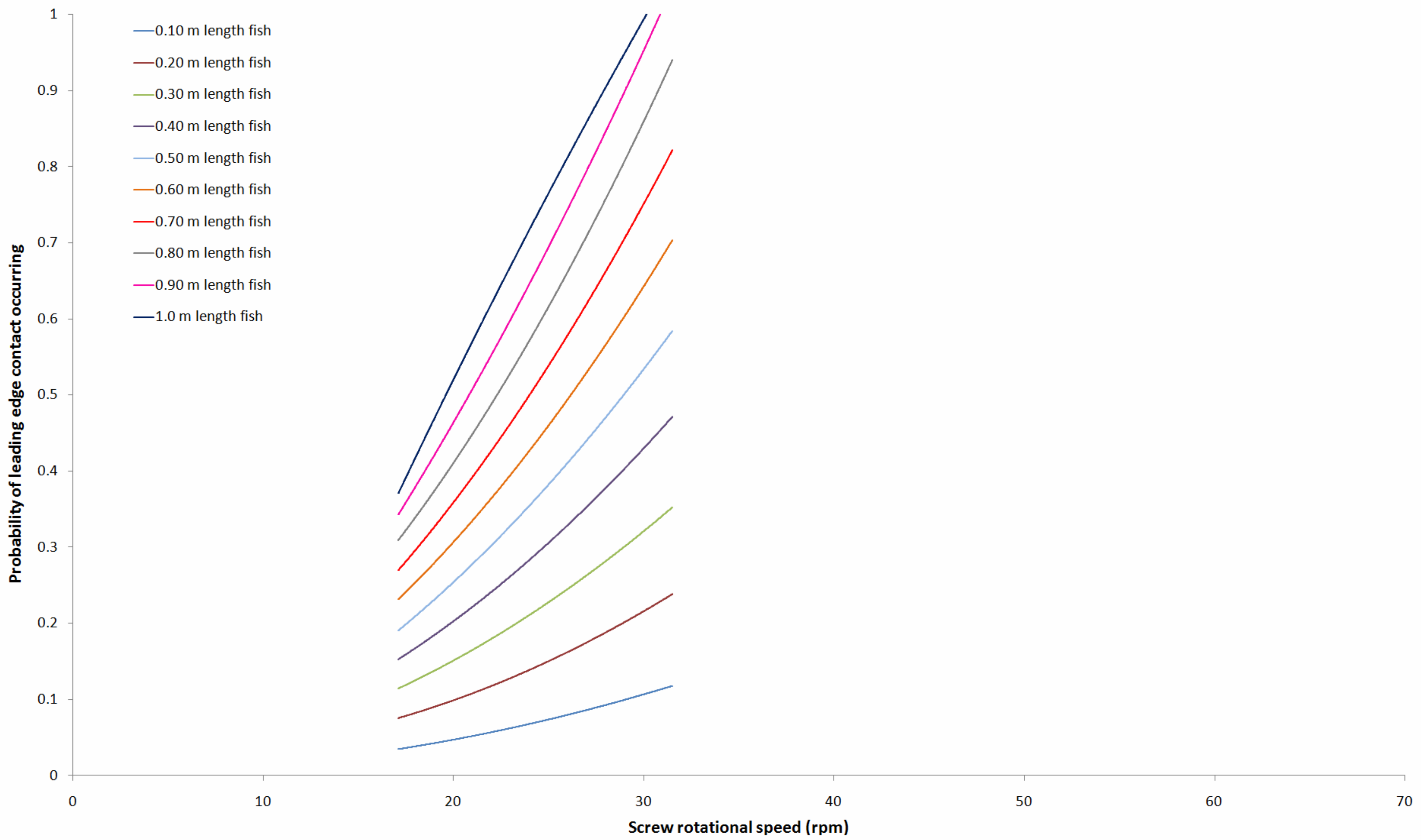

Figure 10: probability of leading edge contact for fish of different sizes passing through screw systems with different rotational speeds and 5 blades. Lines given are second order polynomial best fit lines to the raw data of 34 commercially available screw systems with 5 blades

2.4 Modelled probability of leading edge contact – empirical corrections

The modelled probabilities of leading edge contact detailed in section 2.3 is based on the assumption that fish entering the Archimedean screw turbine do so as inanimate objects of a given length, passing into the screw at the velocity of the water entering the screw. However, there are several factors that will contribute to lower the probability of fish contacting the leading edge, below that predicted purely by the theoretical model and these are as follows:

- Fish will respond behaviourally in order to avoid being struck by the leading edge
- The movement of the blade through the water pushes water ahead of it, which in turn has a tendency to sweep fish out of the way of the leading edge, particularly smaller fish
- The effect of the push of water sweeping fish out of way is magnified by the fitting of rubber bumpers on the leading edges of screws. This increases the cross-sectional area of the leading edge and hence increases the extent to which the leading edges push water ahead of them

Due to these additional factors, that cannot be easily modelled, empirical measurements were taken of live fish trials, in which fish were recorded passing through the Archimedean screw turbine at the River Dart Country Park, in Devon. This screw turbine is 2.2 m in diameter with a typical rotational speed (when passing its maximum flow of 1.1 m^3/s) of 30 rpm.

A total of 195 fish (principally salmon, brown trout and rainbow trout) and 85 eels of a range of sizes were monitored passing through the screw using underwater cameras and the number of fish of each size that contacted a leading edge was recorded. (Round fish and eels were recorded separately as eels have a much higher probability of contacting a leading edge, due to their elongated body-form). The numbers are given in table 3.

Table 3: the number of fish of a range of sizes monitoring passing through the screw at the River Dart country park and the number and proportion observed contacting a leading edge

Fish length range	No. observed passing through screw	No. observed contacting leading edge	Proportion contacting leading edge
0.05 – 0.20 m	100	1	1%
0.20 – 0.40 m	45	4	8.9%
0.40 – 0.60 m	32	5	15.6%
0.60 – 1.0 m	18	4	22.2%

These numbers were then used to create an empirical correction factor, similar to the ‘mutilation ratio’ detailed by Turnpenny *et al.* (2000). The correction factor that was calculated is the relationship between the proportion of fish of each of the size ranges that would be predicted by the model to contact a leading edge and the actual proportion that contacted a leading edge. The predicted numbers were calculated in a similar manner to the work in section 2.3, with the addition that for each length range, each of the 10,000 iterations of the model was run with a random fish length within the length range being considered.

The relationship between the predicted and actual probability of fish contacting a leading edge for the screw turbine at the River Dart country park is given in figure 11. This shows a clear linear relationship between the two probabilities, with the actual probability of contact with a leading edge continuously lower than the predicted probability of contact with a leading edge.

Note that eels have not been investigated further here. While their morphology typically results in a higher risk of injury when passing through a propeller type turbine, in a

Archimedean screw the reverse is true. While eels stand a higher probability of contacting a leading edge (Kibel and Coe, 2008), due to the relatively slow rotational speed of Archimedean screws and elongated body shape of eels, if they contact the leading edge, they tend to 'bend' around the leading edge, before dropping into the first screw chamber. This point is elaborated further in Section 3.

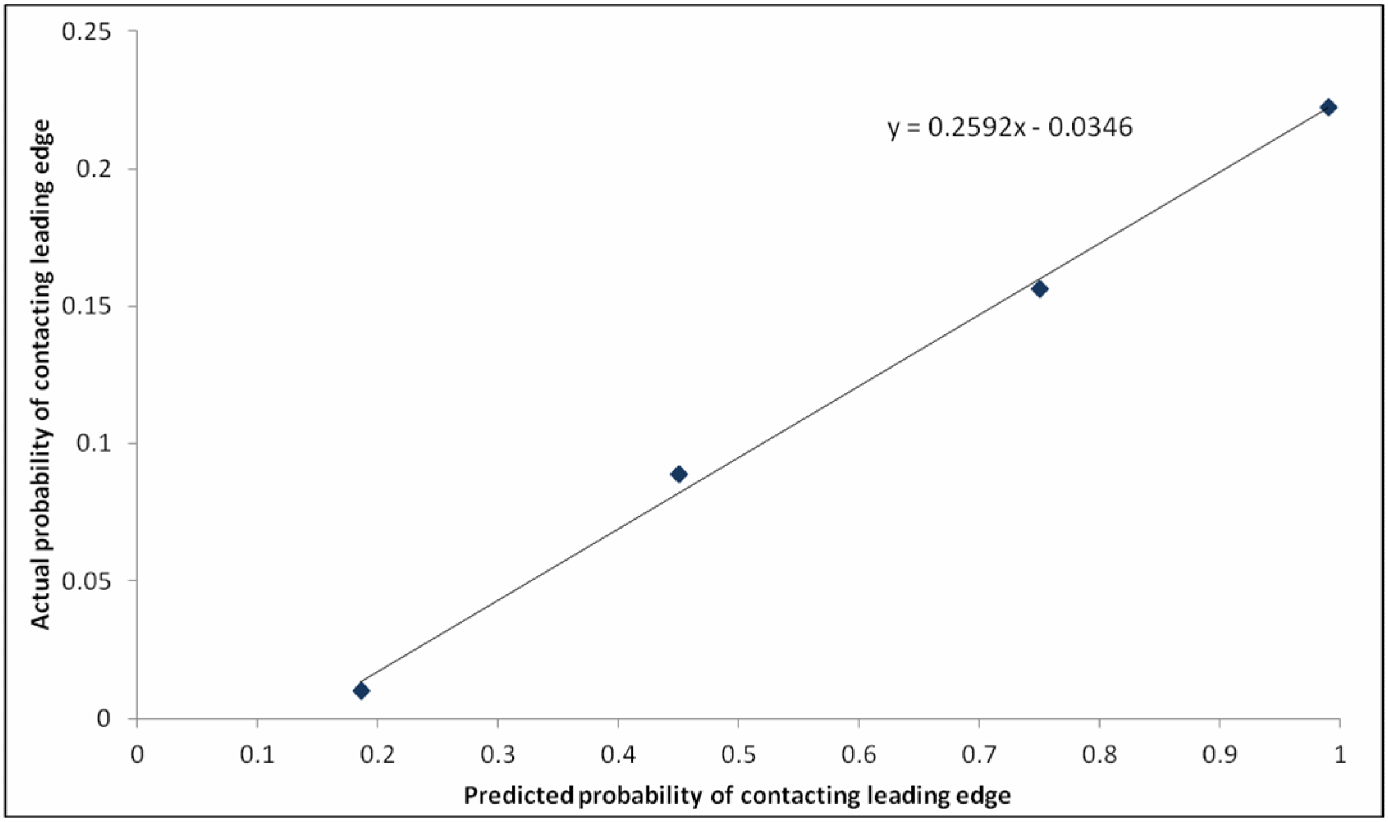

Figure 11: relationship between the predicted and actual probability of fish contacting a leading edge for the River Dart screw turbine (2.2 m diameter, 30 rpm). The four data points correspond to length ranges of 0.05 – 0.2 m, 0.2 – 0.4 m, 0.4 – 0.6 m and 0.6 – 1.0 m. Predicted probabilities of contacting the leading edge were obtained using the model in section 2.3 for a 2.2 m turbine with a flow of 1.1 m^3/s and speed of 30 rpm

The relationship given in figure 11 was then extrapolated to empirically correct the predicted probabilities of leading edge contact occurring for each of the different fish length ranges for all of the 201 screw systems being examined in this report. The results are presented in figures 12-14.

It is immediately clear from the graphs that for systems with a high rotational speed, where the probability of contact with the leading edge occurring is high, the lines tend towards a maximum leading edge contact probability of approximately 0.22, as opposed to 1.0. This is due to the empirical correction, which significantly reduces the likelihood of contact with a leading edge occurring.

As for the modelled, predicted relationships, the over-riding factor appears to be rotational speed (and therefore the screw's size – see figure 3). As screws get smaller, their rotational speeds increase significantly and the velocity of water entering the screw decreases. Both these factors have the effect of increasing the probability that a fish passing into the screw will contact the leading edge.

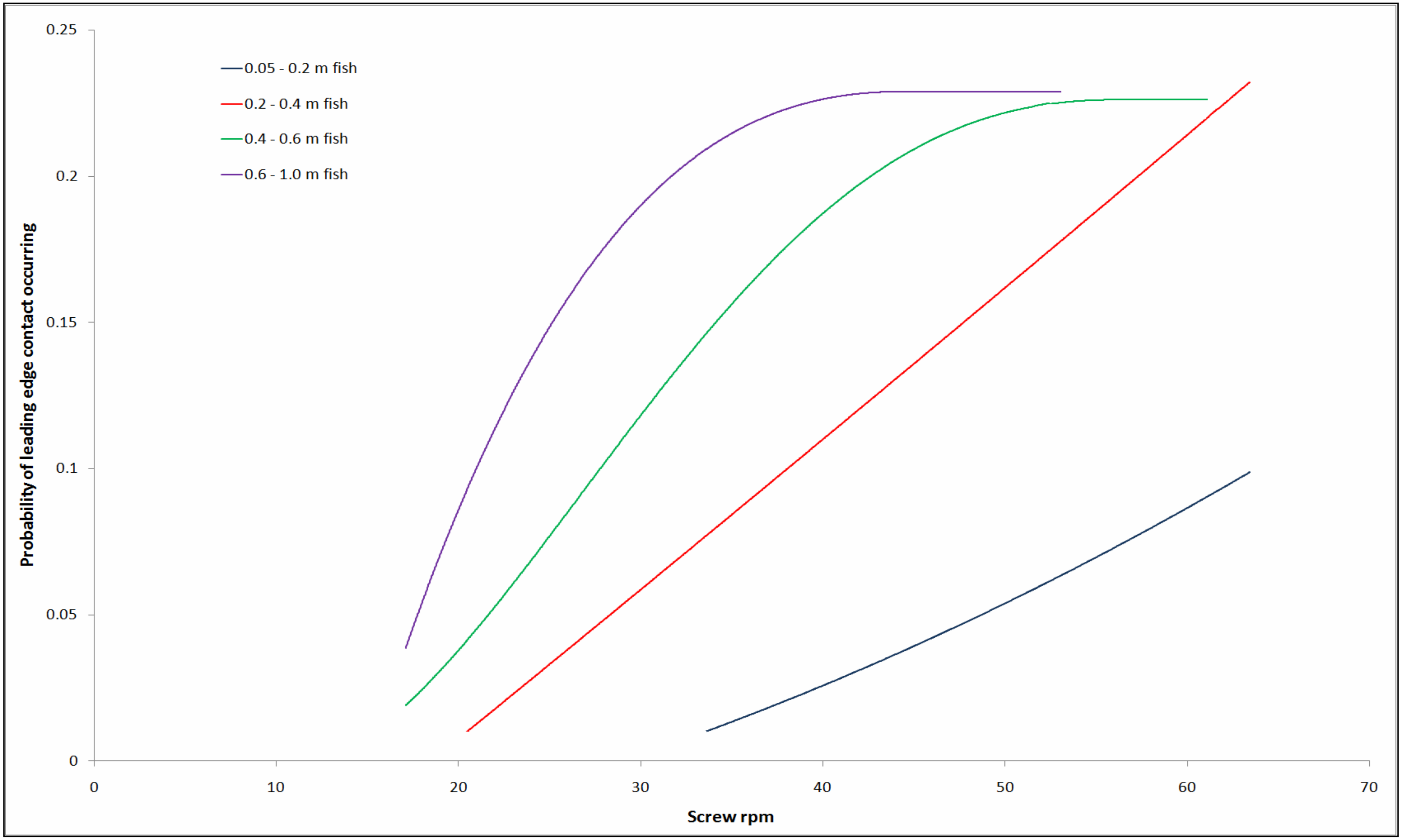

Figure 12: empirically corrected probability of leading edge contact occurring for fish of different sizes passing through 3-bladed screws with different rotational speeds. Lines given are second order polynomial best fit lines to the raw data of 70 commercially available screw systems with 3 blades

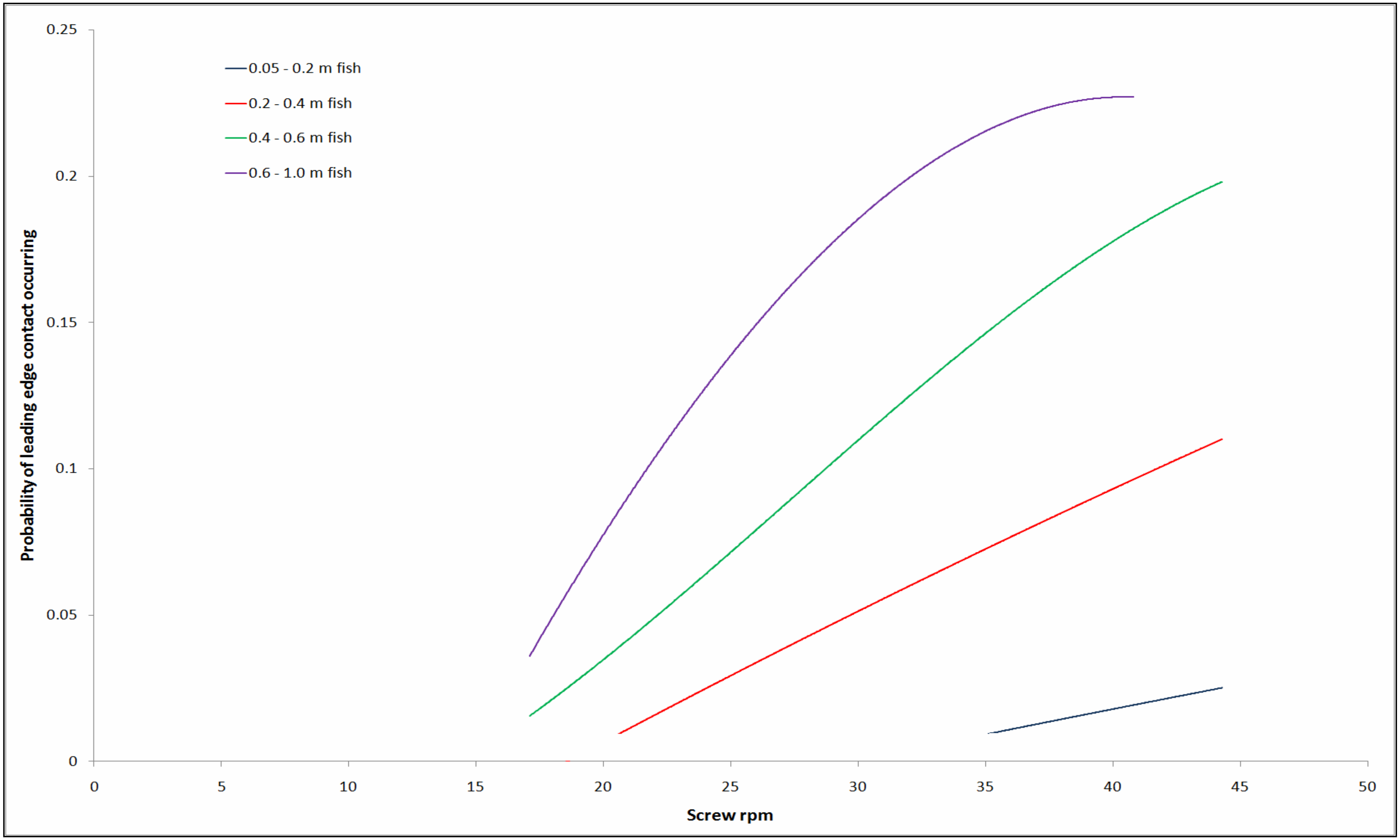

Figure 13: empirically corrected probability of leading edge contact occurring for fish of different sizes passing through 4-bladed screws with different rotational speeds. Lines given are second order polynomial best fit lines to the raw data of 98 commercially available screw systems with 4 blades

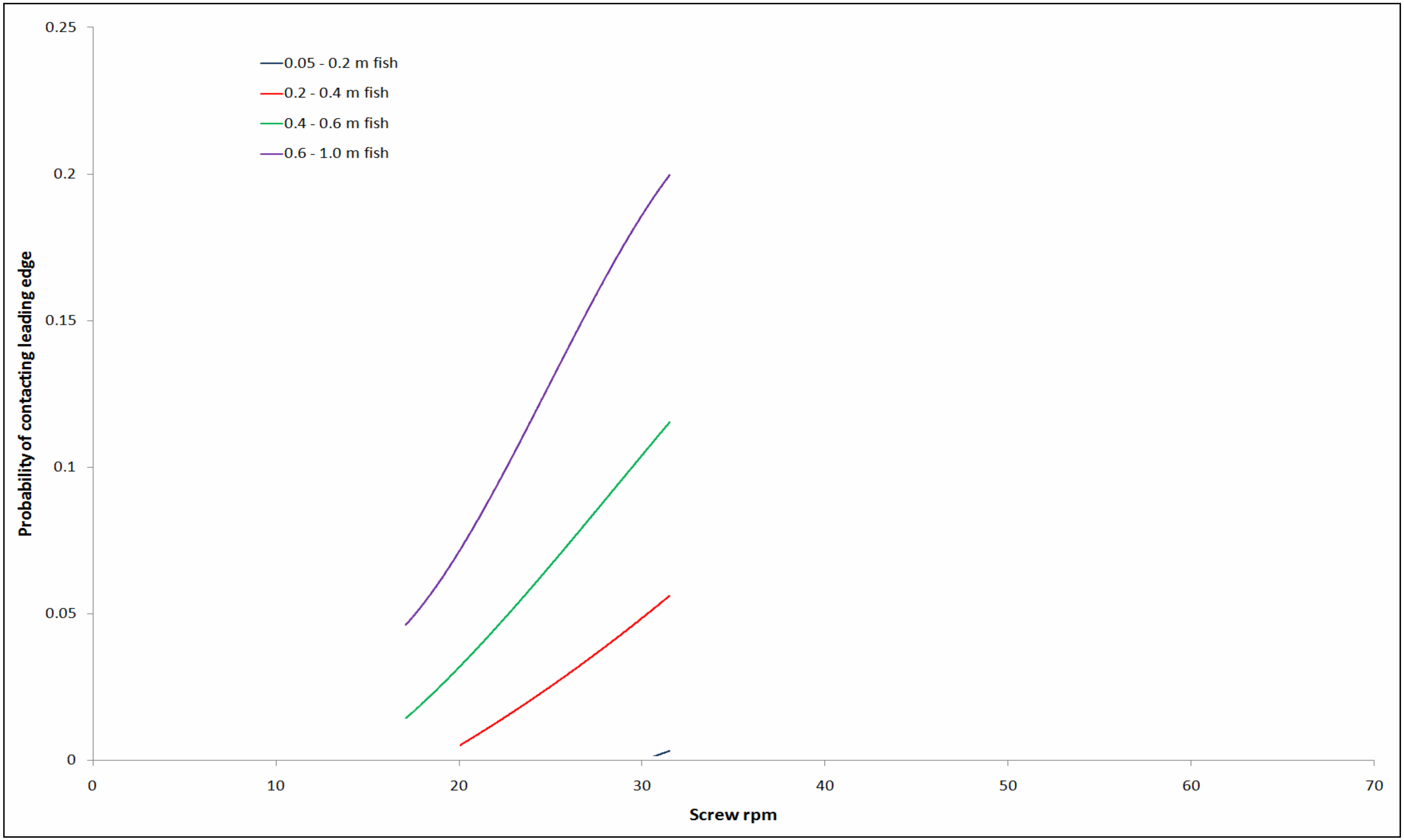

Figure 14: empirically corrected probability of leading edge contact occurring for fish of different sizes passing through 5-bladed screws with different rotational speeds. Lines given are second order polynomial best fit lines to the raw data of 34 commercially available screw systems with 5 blades

It is worth highlighting a couple of key points relating to the graphs presented in figures 12-14. As for the predicted/modelled relationships in section 2.3, for a given rotational speed an increase in the number of blades does not necessarily equate to an increase in the probability of a fish contacting a leading edge. The increase in flow and hence approach speed that is associated with an increase in the number of blades offsets the number of blades and for many systems, compensates for the increase in the number of blades.

The empirically corrected probabilities of leading edge contact occurring for fish of a range of sizes is presented in figure 15 for 3, 4 and 5-bladed systems. This shows clearly that for a given rotational speed, a increase in the number of blades does not equate to an increase in the probability of a fish being struck. This is due to the previously discussed influence of screw flow rates and hence approach velocity.

It should be noted however that for a given flow rate at a proposed scheme, an increase in the number of blades in order to increase the efficiency will result in an increase in the probability of a fish contacting a leading edge (provided that the rotational speed of the system does not change).

A second point worth noting relates to the maximum proportion of fish that may contact a leading edge of a screw (equal to the maximum probability of leading edge contact). It is clear from figures 12-15 that this is approximately 0.22. This maximum is derived using the empirical correction explained previously. The upper limit is defined by the upper point in figure 11, where the prediction from the theoretical model was for 99% of 0.6 - 1.0 m fish to contact the leading edge and the actual figure was 22.2%.

This therefore sets an absolute upper probability limit following empirical correction of 0.22 – 0.23. It is highly likely that the extension of the empirical correction factor to small systems, with associated high rotational speeds may not be appropriate and the probability of large fish contacting the leading edge is higher than 0.22-0.23. However, the empirical correction was developed using the available data from the Dart Country Park. Future work could be conducted deriving a further empirical correction to add to the model from a small screw system in order to increase the accuracy of the derived results.

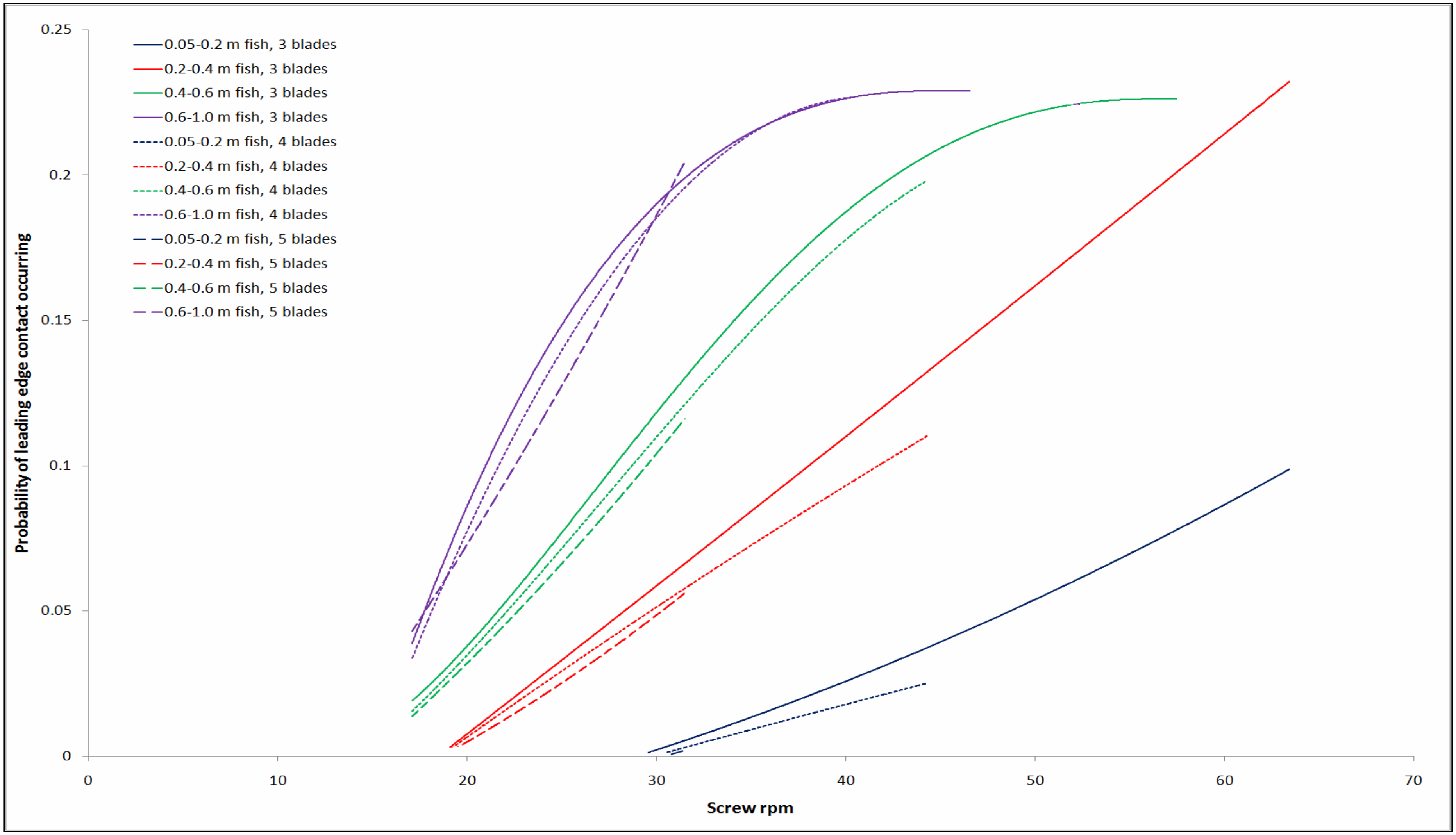

Figure 15: empirically corrected probability of leading edge contact occurring for fish of different sizes passing through 3, 4 and 5-bladed screws with different rotational speeds. Lines given are second order polynomial best fit lines to the raw data of 201 commercially available screw systems. Solid lines correspond to systems with 3 blades, thin-dashed lines to systems with 4 blades and thick-dashed lines to systems with 5 blades

3. Probability of damage occurring

The chance of fish contacting the leading edge increases with the rotational speed of the screw, although not necessarily with the number of blades (see sections 2.3 and 2.4). This increase in rotational speed is typically also accompanied by a reduction in the size of the screw. In terms of the tip speed of the leading edge, this reduction in size compensates for the increase in rotational speed, such that smaller screws with high rotational speeds have slower maximum tip speeds than larger screws with low rotational speeds (see figure 16).

This relationship means that while the probability of a fish contacting the leading edge is higher for a small screw, the likelihood of physical damage occurring is reduced, due to their lower tip speed. Tip speed has previously been shown to be a key determinant of whether injury occurs when a fish is struck by a turbine blade (Turnpenny *et al*, 2000; Ploskey and Carlson, 2004).

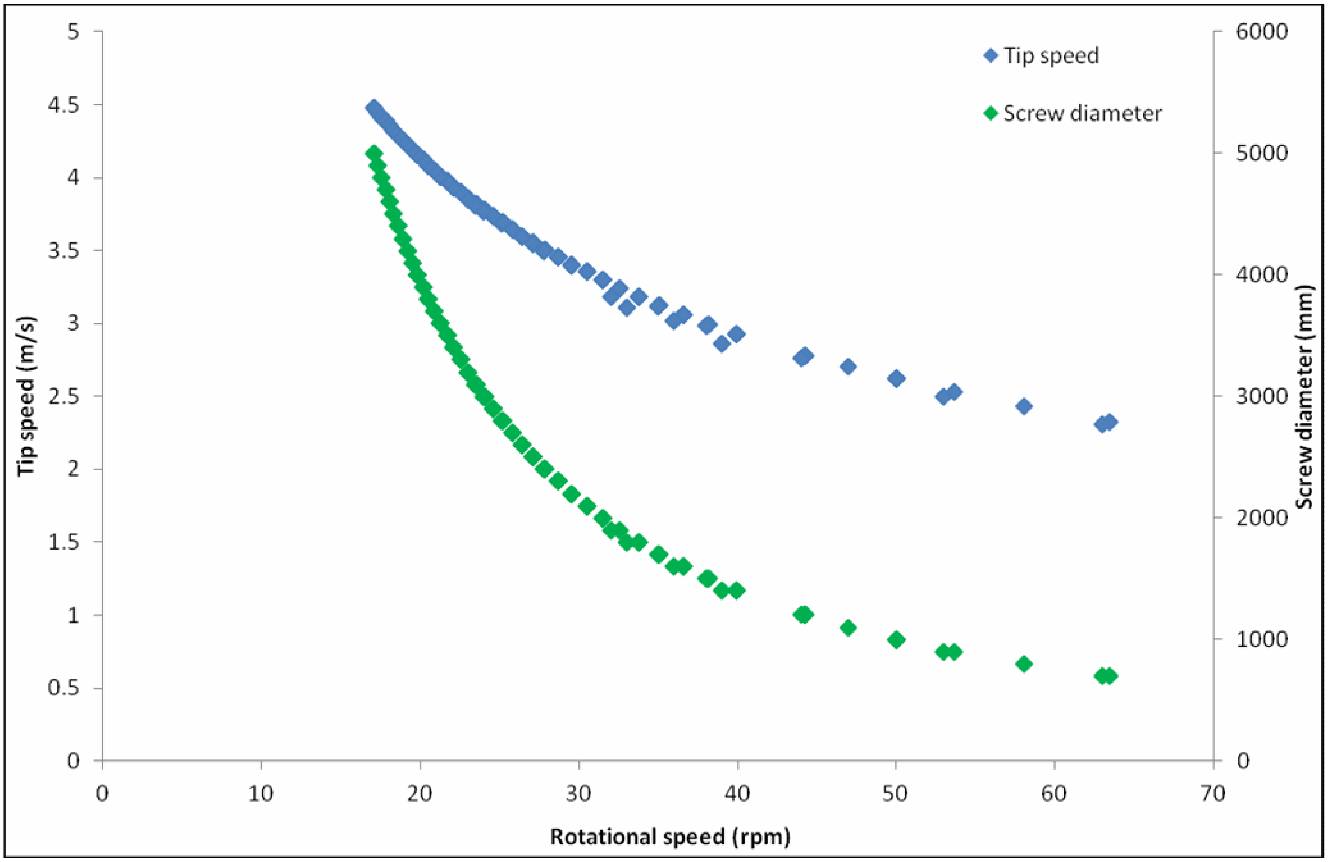

Figure 16: tip speed of a range of commercially available Archimedean screw turbines, depending on screw diameter and rotational speed

Several reports have previously documented that fish passing through an Archimedean screw turbine do not suffer significant damage (see Introduction). In addition, work has been previously carried out (Kibel, Pike and Coe, 2009) demonstrating the use of compressible bumpers to reduce the impact force of fish contacting a leading edge of an Archimedean screw.

This work found a damage threshold of between 2.0 and 2.5 Kg/cm^2 for fish that were struck by the leading edge. By fitting a compressible rubber bumper to the leading edges, the maximum strike force was reduced to 1.2 Kg/cm^2 at a tip speed of 5 m/s, which is above the tip speed of even the largest Archimedean screw that is commercially available (see figure 16). Compressible bumpers are currently recommended to be installed on all larger screws (with tip speeds greater than 3.5 m/s), while hard rubber bumpers are recommended for smaller screws with maximum tip speeds less than 3.5 m/s.

Previous work on other turbines has found damage thresholds in terms of the tip speed above which damage is observed to occur. Monten (1985) looked at injuries to smolts as they passed through Francis turbines and found that injury rates fell below a contact velocity of 4 m/s. Results discussed in Turnpenny *et al.* (2000) show that collision velocities of ≤ 7 m/s in a Kaplan turbine were unlikely to harm fish, with salmon smolts of up to 320 mm in length. The vanes used in such turbines are generally thin – around 2 mm in thickness for Francis turbines and 3 mm in thickness for a Kaplan.

From the results of Kibel, Pike and Coe (2009) a fish of 0.21 kg (which corresponds to a salmon smolt of approximately 250 mm long), struck at 4 m/s by a leading edge profile of 8 mm (the unprotected edge of an Archimedean screw) would be subject to a strike force of 0.75 kg/cm^2 and at 7 m/s would be subject to a strike force of 1.31 kg/cm^2.

Transposing these strike forces to the narrower leading edges of 3 mm and 2 mm for Kaplan and Francis turbines respectively gives equivalent ‘safe threshold’ strike forces as found by Monten (1985) and Turnpenny (2000) of approximately 3 kg/cm^2 and 3.5 kg/cm^2.

Figure 17 presents these approximate safe thresholds relative to the findings of Kibel, Coe and Pike (2009) identifying the strike force to which fish of different sizes would be subject if struck by the largest Archimedean screw (with the fastest tip speed) that can be manufactured (5 m diameter, with a 4.5 m/s tip speed).

This figure shows that the force to which fish would be subjected if struck by the largest/fastest screw fitted with compressible bumpers is always below even the most precautionary threshold of 2.5 kg/cm^2. Although large fish would be subjected to more than the recommended safe thresholds if struck by a leading edge fitted with the hard rubber bumpers, these are not recommended for fitting to screws of 5 m in diameter. The hard rubber bumpers can only be fitted to machines with tip speeds below 3.5 m/s (Kibel, Pike and Coe, 2009).

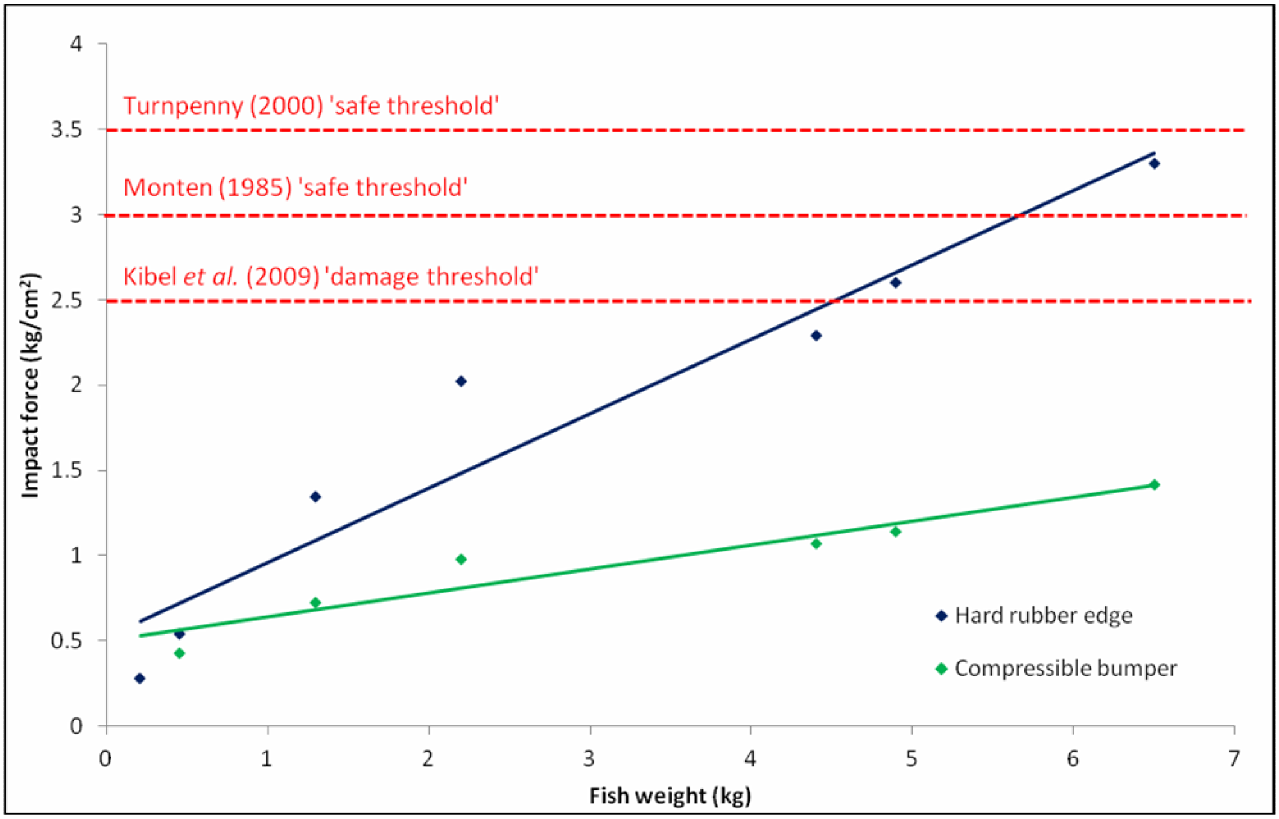

Figure 17: relationship between the weight of a fish and the impact force to which it is subjected if struck by the leading edge of a 5 m diameter Archimedean screw (with a tip speed of 4.5 m/s) with either a hard rubber edge or compressible bumper fitted.

It is important therefore that the risk of damage is placed within the framework of the substantial amount of work already conducted on Archimedean screws and the recommendations and legislation already in place. Screws within the UK are already fitted with rubber extrusions or compressible rubber bumpers in order to reduce the strike force with which they are struck when contacting the leading edge and this already represents a precautionary position, ensuring that any fish that do contact a leading edge are not damaged.

Due to the force of the impact being spread by the compressible bumper or hard rubber bumper, it is highly unlikely that a fish that contacts the leading edge in a screw of any size in the UK will suffer significant damage. This is a critical point, as it means that the issue being considered in this report is not damage *per se*, but the change of delay or prevention of downstream migration.

4. Delays to downstream migration

An important consideration is whether fish are delayed in their downstream migration when they reach an Archimedean screw turbine. The diversion of flows through an Archimedean screw (or any other turbine) removes flows from passing over a weir and/or through a depleted reach. As a result, fish may not be as able to use the usual route downstream and instead the primary downstream migration route becomes passage through the Archimedean screw.

However, if fish are reluctant to enter the screw, downstream migration may be delayed. Such delays could occur for a number of reasons, primarily:

- The time gap between the leading edges is too small and fish are dissuaded from entering the screw
- The probability of fish contacting the leading edge is too high and fish are dissuaded from entering the screw. Such a mechanism is reliant on fish exhibiting behavioural risk aversion and a behavioural judgement that prevents them entering the screw. There is a literature base concerning fishes assessment of risk, primarily with regards to predation (see for example Millinski (1993))
- The size of the screw and particularly the longitudinal gap between helices (i.e. the chamber size) is too small relative to the size of the fish. Again, this relies on fish making a behavioural judgement prior to entering the screw, however, if a large fish were to enter a small chamber size, there is a higher chance of the fish being damaged by being bumped against the sides of the chamber

The risk of delays occurring due to a reluctance of fish to enter the Archimedean screw will be reduced if fish are presented with an alternative, viable route downstream such as a by-wash. There is therefore a need to determine recommendations and guidance as to the circumstances under which an alternative route downstream should be provided. This guidance is outlined below, with reference to the primary reasons that may cause fish to delay

4.1 Time gap between edges and probability of contacting leading edge

It is difficult to quantify the probability threshold that is likely to lead to delays in fish entering the screw and therefore cause delays in downstream migration. The primary concern of fish contacting the leading edge is largely null and void due to the recommendations currently in place concerning the modification of the leading edge. However, fish may delay above the screw, due to behavioural aversions if the time gap between leading edges (see figure 4) is too small, with commensurate high probabilities of contacting a leading edge.

It is extremely difficult to determine a threshold at which fish may delay to avoid a perceived increase in their probability of contacting the leading edge. Despite the quantity of literature on the impact of turbine passage on fish, there is comparatively little on the aversion of fish to entering a turbine.

Thresholds were therefore set as follows:

1) *Delays to downstream migration may occur if the probability of being bumped is greater than 0.2. This is applicable for the largest size of fish that may be expected to pass through a system*
2) *Delays to downstream migration may occur if the temporal gap between leading edges is less than 0.5 seconds*

The first threshold is based on the graphs in section 2.4 and the precautionary approach. Given the insignificant level of damage expected if leading edge contact occurs (see section 3), it is deemed acceptable for 20% of the largest size range of fish passing through the screw to contact the leading edge.

The second threshold is based on empirical observations at the River Dart Country Park screw turbine, where the time gap between leading edges is approximately 0.5 seconds. No significant delays to downstream migration were observed to occur at this site and therefore this interval between leading edges was deemed acceptable.

4.2 Size of the chambers in the screw

It is easier to quantify the guidance relating to the size of the screw chambers as these should be of an appropriate size for the fish within the river system on which the system is being proposed. A clear guidance regarding the size of the chambers in a screw is as follows:

An alternative route downstream should be provided for screws in which either the pitch of the screw (axial distance between helices, or the longitudinal length of each chamber) or diameter of the screw is less than the maximum size of fish that may pass. In addition, coarse bar screening may be necessary to guide large fish into the by wash.

For example, if the maximum size of fish expected to be migrating downstream at a site is 1.0 m; both the pitch and diameter of the screw should be greater than 1.0 m if the screw is to be run without a by-wash of some kind.

The need for a by-wash is reduced and potentially mitigated completely if there is an alternative route downstream that fish may use, for example a notch cut into the weir crest. However, this route must be positioned close enough to the top of the screw for fish arriving at the upstream end of the screw to find it quickly, ideally within 10 - 15 m.

As such, there will be no need for a by-wash on a system where the off-take is immediately beside a weir with an appropriate downstream passage route provided. However, if the screw is situated at the end of a long leat and is of a size such that a by-wash is required, one should be installed alongside the screw.

5. Variable versus fixed speed screw turbines

Currently, Archimedean screws installed in the UK can have either fixed speed or variable speed controls. Licences issued by the Environment Agency typically do not state whether a system should be variable or fixed speed. A fixed speed Archimedean screw works by rotating at a set rpm, which is dictated by the screw's maximum take. As and when the flow through the screw reduces, the depth of water in the screw reduces as well, with lower water depths in the 'buckets' formed between the helices of the screw.

A variable speed Archimedean screw works by rotating at a variable speed and as the flow through the screw reduces, the screw rotational speed slows down. This has the effect of maintaining the upstream head and preventing the depth of water in the screw from reducing. The difference in rpm between fixed speed and variable speed systems is shown using two examples in figures 17 and 18.

Figure 18 presents the rotational speed of a fixed and variable speed 3-bladed screw at a site where the flow characteristics are that of a high base-flow river, with both systems taking a maximum of Q_{mean} (as is typical at many sites), here equal to 3.167 m^3/s and a Hands Off Flow (HOF) of Q95. The flow-duration curve for this hypothetical site is based on actual flow measurements from the River Otter in Devon. It is clear from the relationship presented that the variable machine rpm tracks the screw flow, slowing down as flow decreases. This has the effect of reducing the average rpm at which the variable system is turning, although the maximum rpm for the two machines are the same.

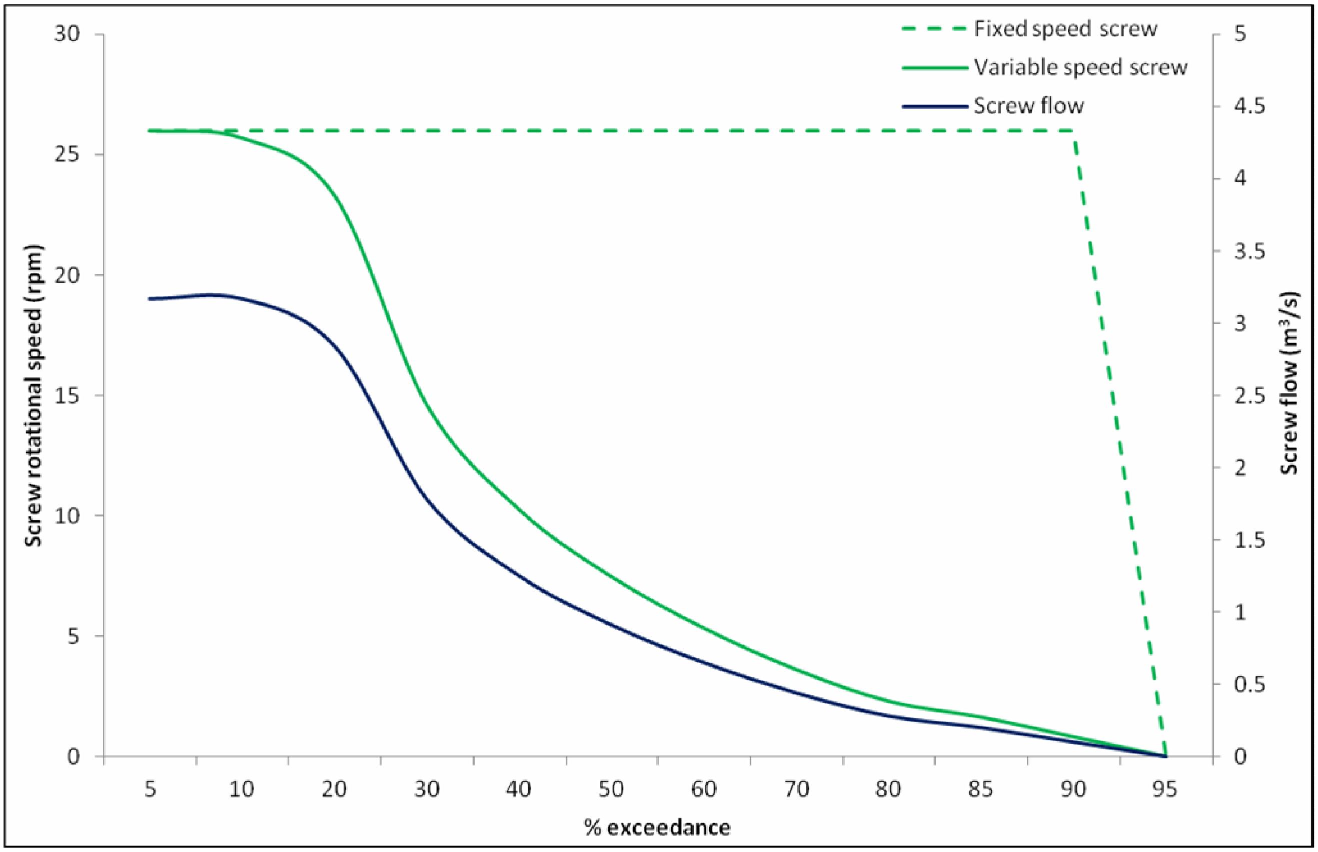

Figure 18: hypothetical relationship between screw flow across the FDC for a fixed speed and variable speed in a high base-flow river, taking up to a maximum of Qmean with a maximum rpm of 26

Figure 19 presents the rotational speed of a fixed and variable speed screw at a site where the flow characteristics are that of a low base-flow river, with both systems taking a maximum of Q_{mean} (as is typical at many sites), here equal to 3.082 m^3/s and a HOF of Q95. The flow-duration curve for this hypothetical site is based on actual flow measurements from the East Lyn in Devon. The relationship presented is similar to that in figure 18, except that the lines are more steep, due to the different form of the FDC.

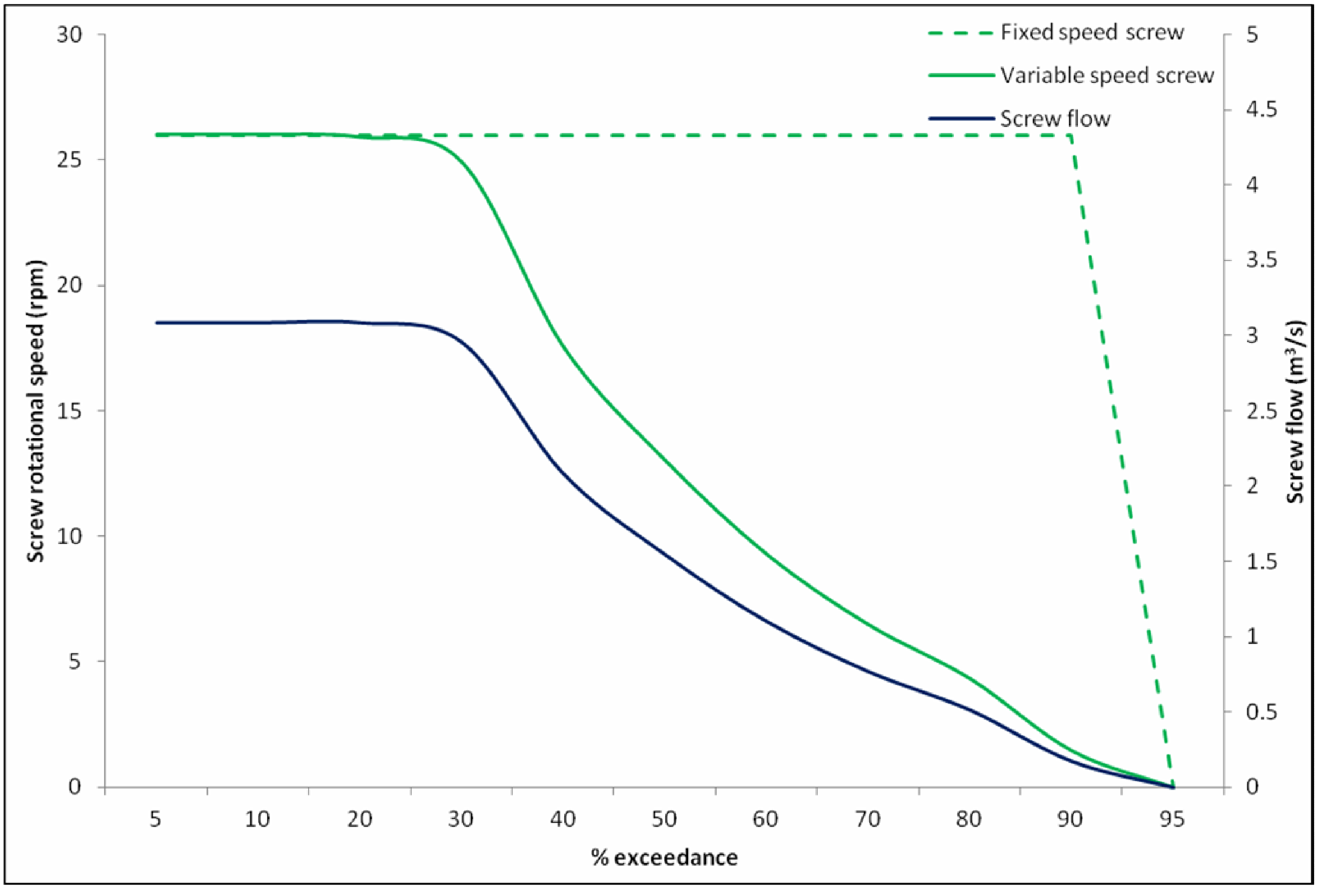

Figure 19: hypothetical relationship between screw flow across the FDC for a fixed speed and variable speed in a low base-flow river, taking up to a maximum of Qmean with a maximum rpm of 26

Due to the lower average rpm of variable speeds, it would be assumed that this translates to a lower probability of leading edge contact occurring for fish passing into the screw. However, as a variable speed screw slows down, the volume of water that the screw is passing also reduces, which therefore decreases the approach velocity into the screw. This has the effect of offsetting the reduction in the rotational speed of the screw.

Figure 20 shows the empirically corrected probabilities of different sized fish contacting a leading edge for the hypothetical screw system on a low base-flow river outlined in figure 18. This shows that the reduction in rotational speed does not equate to a reduction in the probability of leading edge contact occurring, due to the decrease in approach velocity. Rather, the two factors balance each other out almost exactly. This is due to the linear relationships that form the model developed and the linear relationship between a variable screw's rotational speed and the volume of water passing through it.

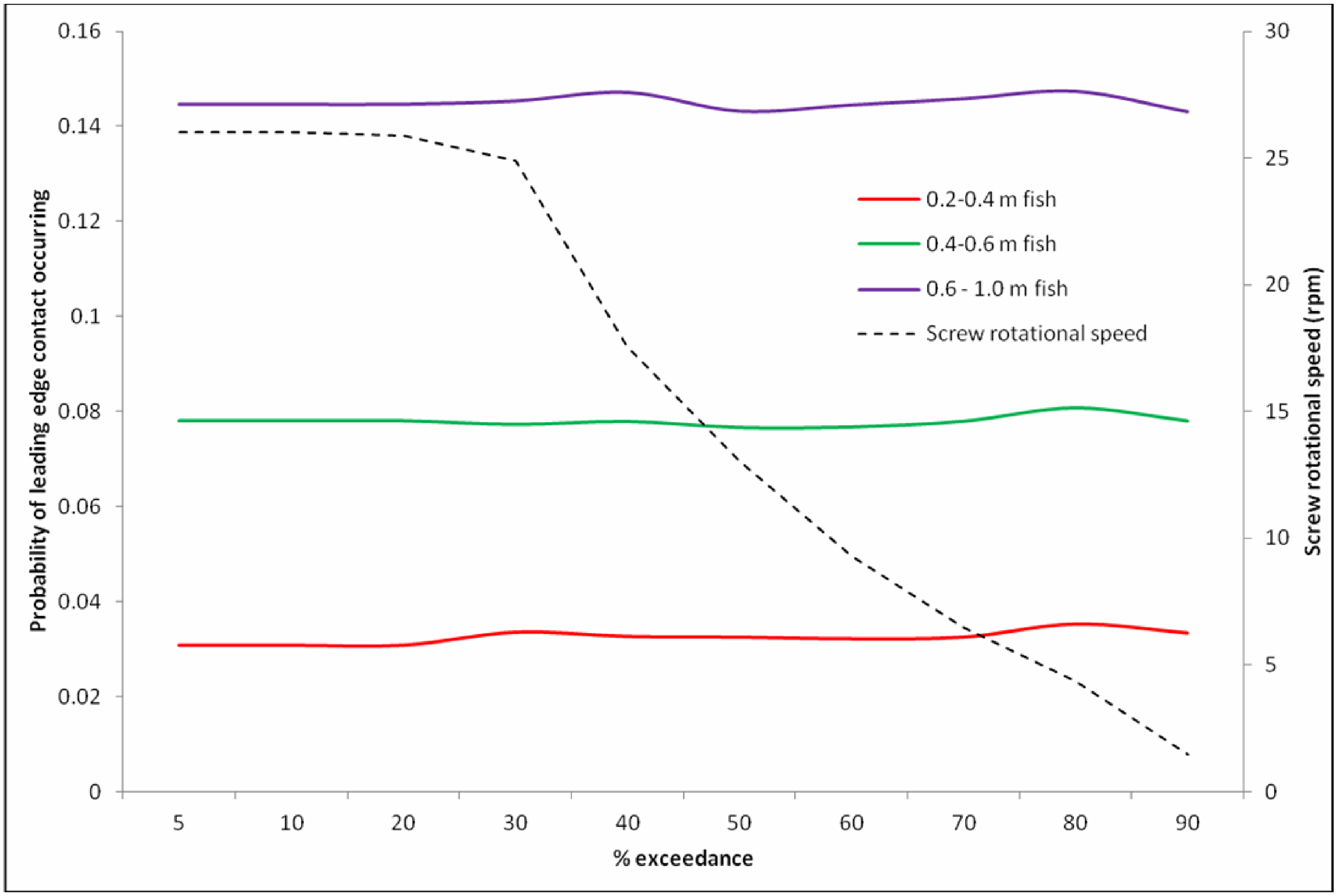

Figure 20: graph showing how the probability of leading edge contact changes for different sized fish passing down a variable speed screw across the FDC, with associated reductions in screw take as the river flow decreases

There is further benefit of variable speed screws, which is that, on average, the rpm of a variable speed screw will be lower which will equate to a higher average gap between blades than on a fixed speed screw designed to take the same maximum flow. Figure 21 presents the time gap between blades for the hypothetical fixed and variable systems in figure 19, on a low base-flow river.

For this system, the fixed speed screw has a gap between blades of 0.76 seconds. While the minimum gap between blades for the variable speed is the same, in a typical year, the *average* gap between blades for the variable speed screw will be approximately 3 seconds, due to the reduced rotational speed of the variable speed screw at below maximum flows.

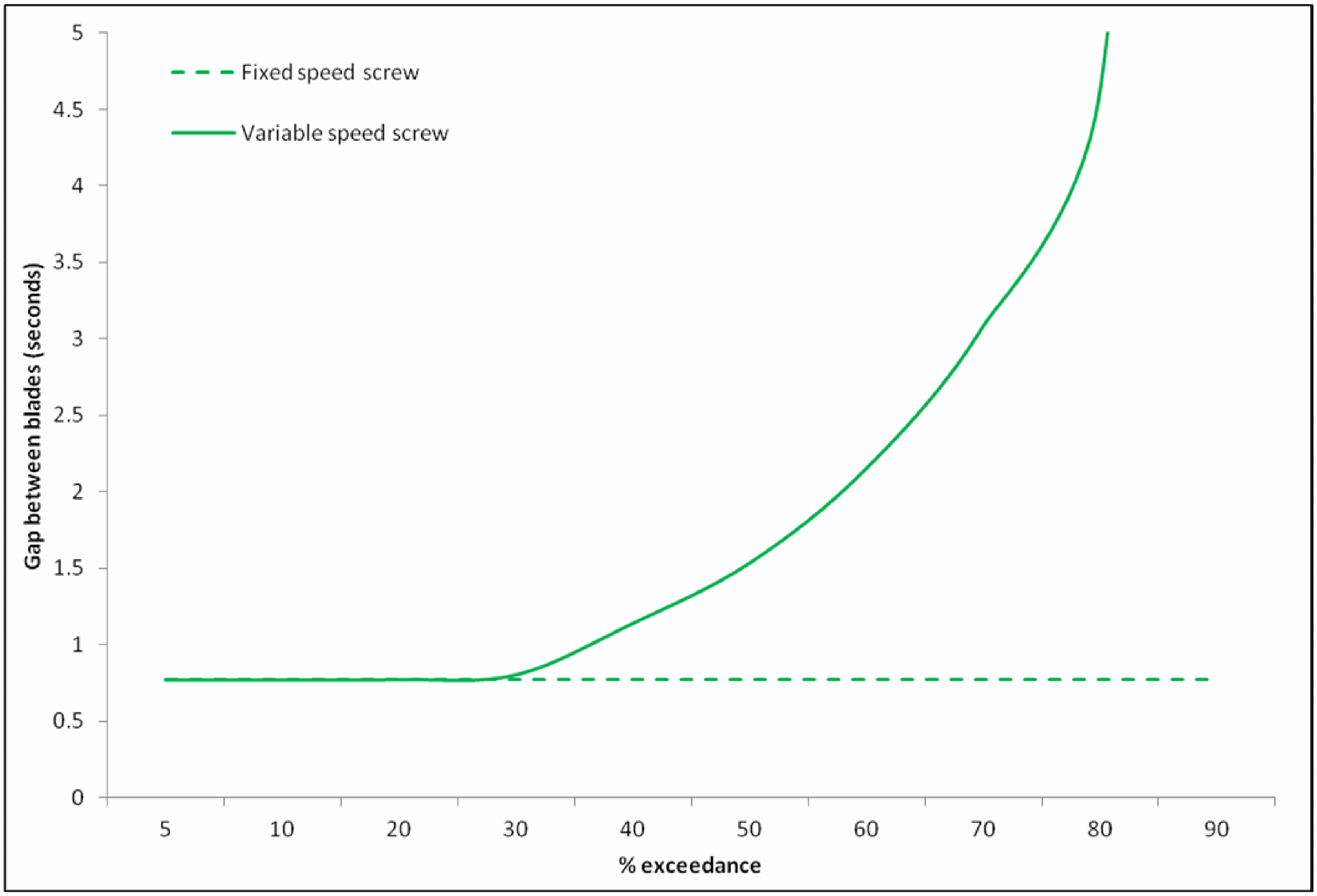

Figure 21: graph showing the gap between blades for fixed and variable speed 3-bladed screws in a hypothetical low base-flow river with a maximum screw rotational speed of 26 rpm

The primary benefits for fisheries of variable speed screws therefore are the maintenance of water depths within the screws by variable turbines that does not occur with fixed speed screws and the average increase in the gaps between blades. The increased depth in variable speed screws will be particularly marked at lower river flows and hence screw takes. This offers a significant advantage as it is likely that fish stand a higher probability of delaying at fixed screw speeds with shallow water depths in the screw itself, shorter time intervals between the helix leading edges and lower water depths in the forebay area.

6. Overall Guidelines

The following are intended as a set of guidelines that can be applied to screw systems being installed across the UK and takes the form of a series of simple look-up tables, based on the relationships derived from the model in section 2.4, and specific thresholds explained in section 4 of this report. The look-up table give concise information as to whether a by-wash is needed for systems with different numbers of blades and rotational speeds.

It should be noted that the look-up table is based on the information about commercial systems that was provided and assume relatively similar hydraulics (flows and therefore approach velocities) for screws from other manufacturers with the same rotational speeds.

The table should be used in a sequential, precautionary manner. It is clear that in some instances the screw rpm (and hence size) above which a by-wash is recommended differs depending on whether the model approach, or gap between leading edges is used. The precautionary approach should therefore be applied and the *lower rpm (equal to the larger screw) used as the threshold above which a by-wash is necessary*. For example, the minimum size for a 4 bladed screw as predicted by the model is given as 1.9 m, 32 rpm. However, using the minimum time gap between blades of 0.5 seconds gives a minimum size of 2.2 m, 30rpm. Applying the precautionary approach, 2.2 m is the minimum size recommended.

Table 4: look-up table for determining the rpm at which a fixed-speed screw will need a by-wash for screw systems with 3, 4 and 5 blades. Note that rpm values in italics in the table indicate that the speed above which a by-wash is needed is above the maximum speed (i.e. below the mimimum size) that is commercially available

3 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required (model approach)	*> 64 rpm*	56 rpm (screw of approx. 0.9 m diameter)	43 rpm (screw of approx 1.2 m diameter)	32 rpm (screw of approx. 1.9 m diameter)
Screw rpm above which by-wash required (time gap between blades approach)	40 rpm (screw of approx. 1.4 m diameter)	40 rpm (screw of approx. 1.4 m diameter)	40 rpm (screw of approx. 1.4 m diameter)	40 rpm (screw of approx. 1.4 m diameter)
4 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required (model approach)	*> 44 rpm*	*> 44 rpm*	*> 44 rpm*	32 rpm (screw of approx. 1.9 m diameter)
Screw rpm above which by-wash required (time gap between blades approach)	30 rpm (screw of approx. 2.2 m diameter)	30 rpm (screw of approx. 2.2 m diameter)	30 rpm (screw of approx. 2.2 m diameter)	30 rpm (screw of approx. 2.2 m diameter)
5 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required (model approach)	NA	*> 32 rpm*	*> 32 rpm*	32 rpm (screw of approx. 1.9 m diameter)
Screw rpm above which by-wash required (time gap between blades approach)	24 rpm (screw of approx. 3.0 m diameter)	24 rpm (screw of approx. 3.0 m diameter)	24 rpm (screw of approx. 3.0 m diameter)	24 rpm (screw of approx. 3.0 m diameter)

The second consideration is the size of the chamber, as considered in section 4.2. While important, this factor is already dealt with effectively by the look-up table. For example, using the guidance outlined in section 4.2, a 3-blade system installed at a site where the maximum size fish is 1.0 m would need a by-wash if the screw was 1.0 m in diameter or less. This corresponds to a screw with an rpm of 50, which is already above the rpm required to have a by-wash in the look-up table. The recommendations in the look-up table above therefore over-rule any requirement based on the diameter of the chambers in the screw.

It is also worth considering whether when a scheme is being proposed and licensed, a variable speed, as opposed to fixed speed, screw turbine is possible, due to the potential benefits gained from maintaining a constant water depth in the forebay area and in the buckets between the screw helices. In addition, the average gap between the leading edge will increase, reducing the chance of delay. Therefore if a variable speed control is proposed, the size of screw above which a by-wash and screen are needed could be smaller (i.e. higher rotational speed).

Figure 22 shows the change in the relative (unit-less) rotational speed and gap between blades for variable-speed screw systems on hypothetical low, medium and high base-flow FDCs (as defined by the EA Good Practice Guidelines for hydropower) with a maximum take of Qmean and HOF of Q95. The graph shows that the rpm (relative to the maximum) decreases rapidly for systems on all three types of river below the turbine satiation point, with an associated significant increase in the relative gap between blades.

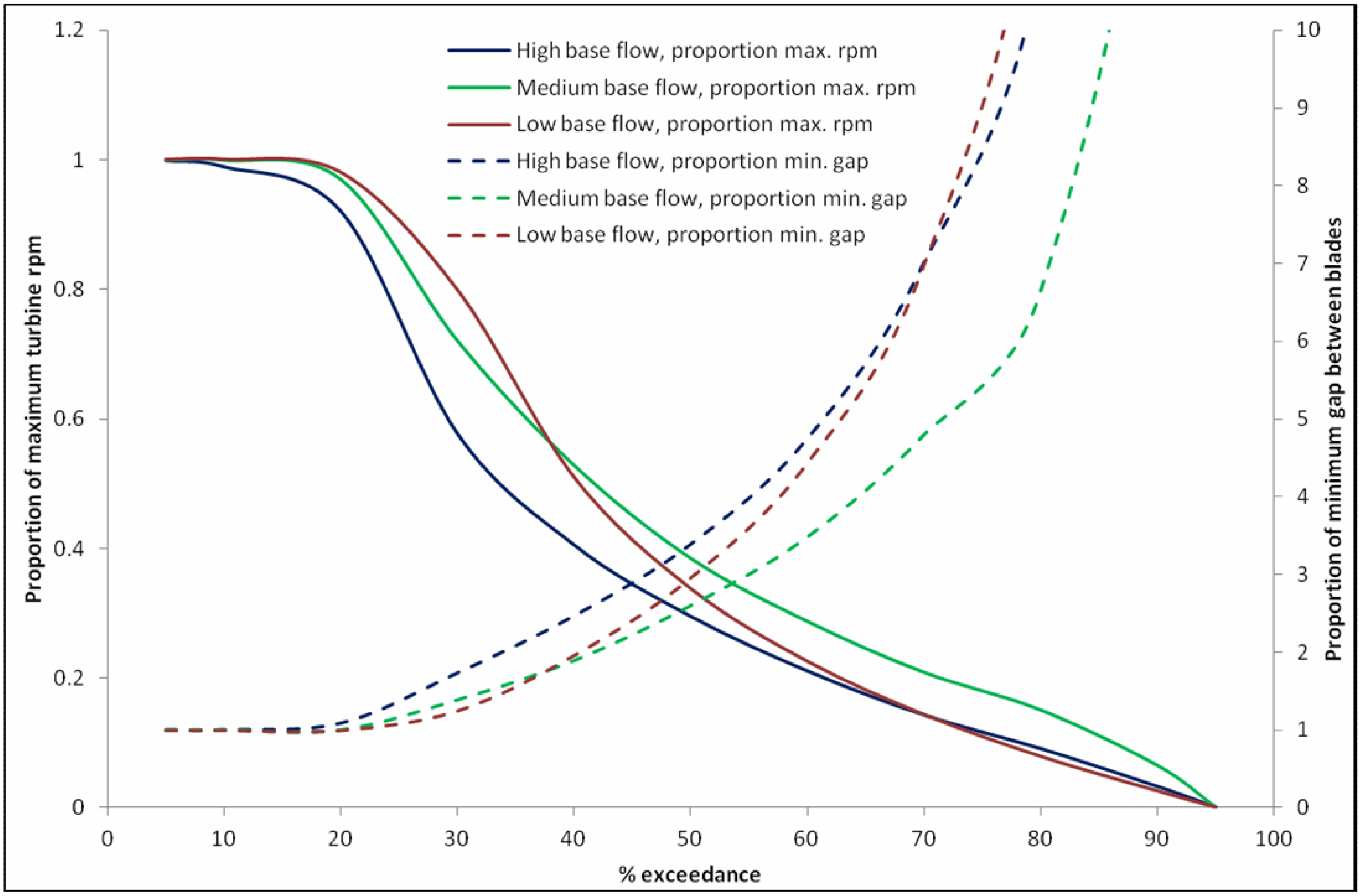

Figure 21: change in the *relative* turbine rpm (solid lines) and gap between blades (dashed lines) for variable-speed Archimedean screws installed on low, medium and high base-flow rivers

It is difficult to determine the exact threshold above which a variable (as opposed to a fixed-speed screw) should have a bywash fitted. The median gap between blades (i.e. the gap between blades when the river flow is Q50) is approximately 2.5 and 3.5 times more than in a fixed speed system, which will still be running at the maximum rpm at Q50. Due to this lower rpm and hence higher gap between blades on variable systems, it would be logical to set the permissible rpm of a variable speed screw higher (and hence the size lower), for a given take.

Taking the precautionary principle (and considering the significant reduction in average rpm of a variable speed screw relative to the equivalent fixed speed system), it is proposed that the the rpm of a variable screw that needs a bywash is *20% higher than the equivalent fixed screw, as detailed in table 4*. This recommendation results in the look-up table as given in table 5.

Table 5: look-up table for determining the rpm at which a variable-speed screw will need a by-wash for screw systems with 3, 4 and 5 blades

3 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required	48 rpm (screw of approx. 1.1 m)	48 rpm (screw of approx. 1.1 m)	48 rpm (screw of approx. 1.1 m)	38 rpm (screw of approx. 1.5 m)
4 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required	36 rpm (screw of approx. 1.6 m)	36 rpm (screw of approx. 1.6 m)	36 rpm (screw of approx. 1.6 m)	38 rpm (screw of approx. 1.5 m)
5 BLADES	**Maximum size range of fish found at site**			
	0.05 – 0.2 m	0.2 – 0.4 m	0.4 – 0.6 m	0.6 – 1.0 m
Screw rpm above which by-wash required	29 rpm (screw of approx 2.3 m)	29 rpm (screw of approx 2.3 m)	29 rpm (screw of approx 2.3 m)	29 rpm (screw of approx 2.3 m)

There are benefits for the operation of the system as well, as by maintaining a constant upstream head that does not decrease as flows decrease, an increase in overall screw efficiency is gained.

6.1 Recommendations for further work

The look-up tables given are precautionary and based on the available data at the time this report was produced. It would, however, be advantageous to conduct further work to assess whether fish delay above small Archimedean screw systems. This work would provide further empirical evidence as to the interaction between fish and small screw systems with high rotational speeds. In addition, as previously mentioned, it would allow the empirical correction factor within the report to be adjusted and refined accordingly. Until this work is undertaken however, we advise that the recommendations given are followed.

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