ANGUILLES-OUVRAGES

PROGRAMME NATIONAL DE RECHERCHE-DEVELOPPEMENT 2008-2009

TEST DU MIGROMAT®, BIOMONITEUR DE PREDICTION DES PERIODES DE DEVALAISON DE L'ANGUILLE ARGENTEE

Experimentation à Killaloe sur la rivière Shannon (Irlande) – 2008-2010 -

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Depuis plusieurs décennies, l'anguille européenne (Anguilla anguilla) présente de nets signes de déclin de son abondance sur l'ensemble de son aire de répartition (Dekker, 2004). Elle fait aujourd'hui partie des espèces menacées et au vu des bilans la situation est aujourd'hui devenue critique. Plus qu'un facteur en particulier, c'est une multiplicité de facteurs qui sont à l'origine de cette diminution continue. Il est donc essentiel de réduire significativement les pressions qui pèsent sur le stock (pêche et aspects environnementaux), mais aussi d'intervenir sur les obstacles à sa libre circulation qui constituent l'un des principaux facteurs limitant son aire de répartition en milieu continental avec des blocages à la montaison et des dommages lors de la dévalaison (dommages et mortalités suite au passage au travers des turbines).

Afin de restaurer le stock d'anguille, l'Union européenne a pris des mesures de protection au travers du règlement CE n° 1100/2007 du 18 septembre 2007. Le récent règlement européen pour la reconstitution du stock d'anguilles a défini un objectif d'atteindre un taux d'échappement de géniteurs équivalent à 40% de la biomasse « pristine » (état naturel sans pression anthropique impactant le stock).

Le Ministère de l'Ecologie, de l'Energie, du Développement Durable et de l'Aménagement du Territoire ainsi que le Ministère de l'Agriculture et de la Pêche ont été chargés de mettre en place un Plan de Gestion national pour la reconstitution du stock d'anguilles comportant des mesures sur les différents facteurs de mortalités anthropiques. Afin de mener à bien ce Plan de Gestion, un Comité National Anguille a été mis en place, ainsi que plusieurs groupes de travail thématiques, dont le groupe de travail « Ouvrages ».

Le **groupe de travail « Ouvrages »** a rendu un rapport validé par le Comité National le 9 janvier 2008. Celui-ci a conclu notamment à l'intérêt de la mise en œuvre d'un programme de Recherche et de Développement qui a pour objectif la mise en œuvre d'un certain nombre d'actions visant à acquérir une meilleure connaissance du comportement et des rythmes de dévalaison de l'anguille, à évaluer l'impact des aménagements hydroélectriques à la dévalaison (mortalités dans les turbines et impacts cumulés des aménagements sur un axe donné), à développer et évaluer de nouvelles techniques visant à réduire les mortalités dans les turbines (prises d'eau ichtyocompatibles, turbines ichtyophiles, biomoniteurs, barrières comportementales).

Dans ce contexte un certain nombre **d'actions communes de Recherche et Développement** sur le franchissement des ouvrages par l'anguille européenne ont été engagées en 2008 et 2009, actions qui ont fait l'objet d'un **accord cadre** signé par les principaux acteurs : Electricité de France, France Hydroélectricité, GDF-SUEZ, la Compagnie Nationale du Rhône, la Société Hydroélectrique du Midi, l'ADEME et l'ONEMA.

La présente étude est issue de cet accord-cadre et constitue l'**action n°10** de ce programme R&D.

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RESUME

Une des solutions potentielles aux mortalités résultant du transit des anguilles argentées dans les turbines de centrales hydroélectriques consiste à arrêter ou à réduire le fonctionnement des turbines. Ces modifications de fonctionnement peuvent entraîner des pertes de production très conséquentes si elles sont appliquées durant toute la période de migration qui dure plusieurs mois en Europe. Pour pallier ce problème, il serait intéressant de disposer de méthodes permettant de prévoir les périodes de dévalaison de façon à n'effectuer les manœuvres d'usine que dans ces seules périodes. A cet effet, un biomoniteur, le MIGROMAT®, permettant de prévoir les périodes de dévalaison est proposé par le bureau d'étude allemand IfAÖ (Institut für angewandte Ökologie). Dans son principe, ce biomoniteur consiste à mesurer l'activité de locomotion d'anguilles maintenues en captivité dans des bassins et à prévoir, par analyse du signal enregistré, les périodes de dévalaison imminentes. Le MIGROMAT®, a été installé à l'amont immédiat de la pêcherie d'anguille argentée de Killaloe sur la rivière Shannon en Irlande et ses capacités de prévision comparées aux captures effectuées par la pêcherie fonctionnant en continu durant plusieurs semaines sur deux saisons de migration, 2008-2009 et 2009-2010. L'efficacité du MIGROMAT® s'est avérée relativement faible : prévision de 14.3–20.8% et 18.1–29.1% de la dévalaison respectivement en 2008/2009 et 2009/2010. Cette efficacité s'avère insuffisante pour satisfaire les exigences de la règlementation européenne. Les causes principales de l'efficacité partielle du Migromat® résultent essentiellement du fait que d'une part, les alertes ont été générées essentiellement durant les pics de migration et non avant leur arrivée (i.e. absence de détection pré-migratoire) et que d'autre part une proportion significative de la migration n'a pas été détectée.

Mots clés: Biomoniteur, Migromat®, anguille argentée, prédiction dévalaison.

ABSTRACT

One potential solution to mortalities resulting from the passage of silver eels through hydro turbines is to stop or reduce the turbine operation. These operations may result in very substantial losses in production if they are applied throughout all the migration period lasting several months in Europe. To overcome this problem, it would be useful to have methods to predict the downstream migration periods to reduce the operation of hydro plants only during those periods. For this purpose, an early warning system, the MIGROMAT®, able to predict the downstream migration periods is proposed by the German consulting firm IFAO (Institut für angewandte Ökologie). In its principle, this biomonitor measures the activity levels of captive eels and provides, by analyzing the recorded signal, an early warning of the migration periods. The MIGROMAT® was installed immediately upstream of the Killaloe silver eel fishery on the River Shannon in Ireland and its predictive capability compared to catches of the fishery operating continuously for several weeks on two migration seasons , 2008-2009 and 2009-2010. The effectiveness of the MIGROMAT ® appeared relatively low: 14.3-20.8% and 18.1-29.1% forecast of downstream migration respectively in 2008/2009 and 2009/2010. This efficiency would not be sufficient to satisfy the requirements of the European regulation. The effectiveness of the Migromat® system was likely reduced as alerts were generally received during, rather than before, peak migration events (i.e. lack of pre–migration prediction) and a significant proportion of silver eels migrated undetected.

Key words: Biomonitor, Migromat®, silver eel, prediction, downstream migration, early warning system.

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SYNTHESE OPERATIONNELLE

• Ce rapport résume les résultats de deux années d'étude sur le Migromat®, dispositif de détection précoce des pics de dévalaison de l'anguille. Cette etude a été réalisée en collaboration entre des chercheurs irlandais et français..

• La capacité de prediction des pics de dévalaison de l'anguille argentée Anguilla anguilla par le dispositive a été évaluée par comparaison avec les captures journalières effectuées par la pêcherie de Killaloe sur la rivière Shannon en Irlande.

• L'expérimentation a été conduit Durant deux saisons de pêche à l'anguille argentée (2008/2009 et 2009/2010).

• Diverses interprétations des alertes générées par le Migromat® selon plusieurs modèles analytiques ont été effectuées en utilisant les statistiques de capture de la pêcherie de Killaloe.

• Les quantités d'anguilles argentées qui auraient été "sauvées" (par arrêt de turbines) en évitant leur passage dans une centrale hydroélectrique virtuelle installée au droit de la pêcherie de Killaloe ont été analysées.

• Par ailleurs, l'impact des alertes du Migromat® sur la production hydroélectrique (perte de production par arrêt des turbines) ainsi que l'efficacité de modèles de prédiction alternatifs (p. ex. prédiction par les pêcheurs professionnels ou les phases lunaires) sont présentés et discutés.

• Les résultats de cette étude amènent à la conclusion que, dans le contexte de la rivière Shannon, le Migromat® n'est pas un outil efficace de prédiction de la migration de l'anguille argentée.

• Les quantités d'anguilles argentées capturées en se basant sur les alertes Migromat® ont été relativement faibles (14.3–20.8% et 18.1–29.1% de la capture totale respectivement en 2008/2009 et 2009/2010). Ells s'avèrent insuffisantes pour satisfaire les exigeances du Plan National de Gestion de l'Anguille en Irlande.

• Les causes principales de l'efficacité partielle du Migromat® résultent essentiellement du fait que d'une part, les alertes ont été générées essentiellement durant les pics de migration et non avant leur arrivée (i.e. absence de détection pré-migratoire) et que d'autre part une proportion significative de la migration n'a pas été détectée.

• Cependant, le fait que les alertes du Migromat® se traduisent par une perte de production hydroélectrique de seulement 5.1–7.4%, est prometteur et laisse à penser qu'il serait intéressant de poursuivre les investigations pour améliorer la capacité de prédiction du dispositif.

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Final Report on the Operation of the Migromat® at Killaloe, Ireland (2008–2010)

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Contents

Executive Summary

- This report summarises the results of a two year collaborative project on the Migromat® early warning system, involving French and Irish researchers.

- The predictive capacity of the system, to signal downstream migrations of silver eels *Anguilla anguilla*, was evaluated by reference to the daily catches obtained at Killaloe eel weir, on the Irish River Shannon.

- The experimental project was undertaken during two silver eel fishing seasons (2008/2009 and 2009/2010).

- Various Migromat® alert interpretations and analytical models were evaluated using Killaloe silver eel catch statistics.

- The quantities of silver eels that could have been 'saved' (by turbine shutdown) from entering a hydropower station theoretically located at the eel weir, were analysed.

- Likewise, the impact of Migromat®–signalled turbine shutdown on hydropower production (*i.e.* loss of generation), and the effectiveness of alternative prediction models (*e.g.* fishermen's predictions, lunar phase) are presented and discussed.

- The results of this project indicate that Migromat® is not an effective biomonitoring tool for prediction of downstream silver eel migration at this site.

- The quantities of silver eels captured, based on Migromat® alerts, were relatively low (14.3–20.8% of the total catch in 2008/2009 and 18.1–29.1% of the total catch in 2009/2010) and would not be sufficient to satisfy the requirements of Ireland's National Eel Management Plan.

- The effectiveness of the Migromat® system was likely reduced as alerts were generally received *during*, rather than *before*, peak migration events (*i.e.* lack of pre–migration prediction) and a significant proportion of silver eels migrated undetected.

- However, the fact that Migromat® alerts (in 2009/2010) corresponded to just 5.1–7.4% loss of generation is promising and further development may be improve the predictive capacity of the system

1. Context

The evaluation of alternative methodologies for investigating and understanding the considerable variation in patterns of silver eel migration is important for a variety of reasons. The European eel is undergoing a serious collapse in its populations throughout the geographical range it occupies, and the factors involved are poorly understood (ICES, 2009). The EU plan for recovery of the eel stocks (European Council Regulation No. 1100/2007) requires each Member State to implement Eel Management Plans. These plans are intended to increase eel spawner escapement from river basins. The objective is to try and ensure that escapement spawner biomass is restored to levels similar (>40%) to those that occurred when pristine environmental conditions existed. Therefore, obstacles and threats to the seaward migrating silver–phase (pre–spawner) eels in European rivers must be investigated and, where possible, mitigation measures must be developed and implemented. The adverse effects of hydropower generating facilities, through delayed migration, and mortality or injuries caused by impingement on screens or turbine passage, has been highlighted by the development of eel management plans in many countries (e.g. Ireland, France, Germany and Sweden). Development of river specific or more generally applicable spawner conservation measures is a priority research task for all involved in providing advice on eel conservation protocols that could be adopted at hydropower plants. Capacity to predict peak migrations could allow for management of water resources in a manner that reduces the impact of hydropower on eels, for example by opening spillways at critical times, and could also provide a better knowledge base for other eel conservation measures.

The evaluation of a specific eel biomonitoring technology (Migromat® early warning system) in this project involved international collaboration by researchers. The associated networking, and exchanges of information, was very productive and will hopefully be continued. The project partnership consisted of the National University of Ireland, Galway (NUIG), Electricity Supply Board (ESB), Électricité de France (EDF), Office National de l'Eau et des Milieux Aquatiques (ONEMA) and France Hydroelectricité, with the Institut für Angewandte Ökologie (IfAÖ) as contractors. The membership of the project steering group and other contributors to the project are indicated in Appendix 1. It is anticipated that the results presented below will stimulate wider discussion than is required for reaching a conclusion on the effectiveness of one particular eel migration biomonitoring tool.

2. Migromat® early warning system

2.1 Principles and description

Migromat® (Adam, 2000; Bruijs & Durif, 2009; Bruijs *et al.,* 2009) is an early warning system which uses the activity levels of captive eels to predict peak silver eel migration events. The overall aim of the project was to evaluate the effectiveness of the Migromat® system for prediction of peak silver eel migration events, by reference to the daily catches obtained at Killaloe eel weir on the River Shannon, Ireland. The Migromat® equipment was supplied and operated, remotely, by IfAÖ under contract to EDF and France Hydroelectricité. The experimental site and engineering works associated with installation of the Migromat® were provided by ESB who, in conjunction with NUIG, also provided on-site supervision and maintenance support for the project. NUIG undertook scientific monitoring and data analysis, in partnership with EDF and ONEMA.

The Migromat® system consists of two tanks, each with a capacity of 5 m^3. The tanks are divided into five compartments of 1 m^3 volume, each connected by an opening of 30 cm in diameter (Fig. 1). A PIT antenna loop is inserted in each opening between compartments and perforated lids allow natural conditions to be perceived by the eels. Each tank is continuously pumped with river water.

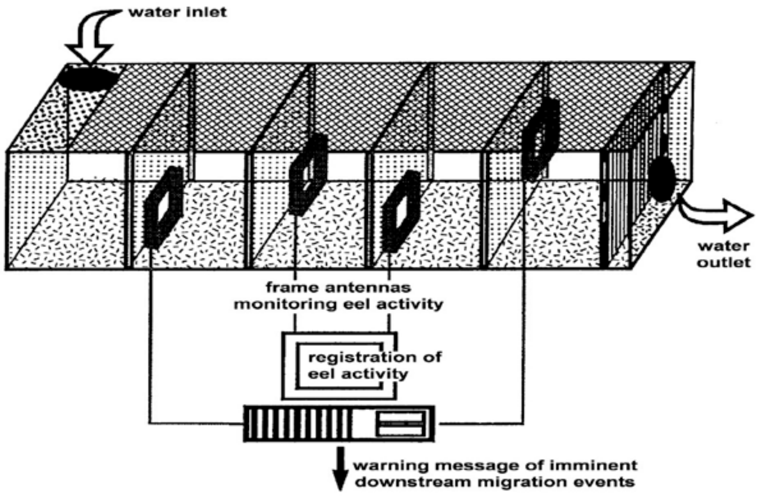

Figure 1. Schematic diagram of the Migromat® system, showing one of the tanks (Bruijs *et al.*, 2009).

The displacement of PIT-tagged eels between compartments, recorded by the antennas, indicates an increase in activity levels. Two passages of an eel within 2 mins is considered an activity point, and prediction of eel migration by the system is based on hourly activity in the context of normal circadian rhythm (Bruijs *et al.,* 2009). An increase in activity points (above a threshold) indicates an upcoming eel migration (*i.e.* pre–migratory restlessness), and an alert is triggered (Bruijs *et al.,* 2009).

3. Migromat® at Killaloe

3.1 Installation

A Migromat® system was installed at Pier Head, Killaloe, Ireland (Fig. 2) in September 2008, and the experiment was conducted over two silver eel migration seasons (2008/2009 and 2009/2010). The experiment site was located on the main channel of the River Shannon, 1 km downstream of the outlet of Lough Derg and 0.7 km upstream of Killaloe eel weir. The River Shannon, the longest river in Ireland, has a main channel length of 359 km, including the estuary, and drains a total area of 14,000 km^2. The Shannon is regulated for hydroelectricity generation at Parteen weir (5 km downstream of Killaloe), which diverts the main flow of water via a 13 km headrace canal to Ardnacrusha hydropower station (86 MW). Mean annual discharge from the River Shannon is $186 m^3 s^{-1}$ (McCarthy *et al.,* 2008).

Figure 2. The Migromat® system located at Pier Head, Killaloe, Ireland.

3.2 Biological operation

During the two phases of the project, eels were provided by NUIG to IfAÖ for stocking of the Migromat® system. At the beginning of each phase, eels were anaesthetised and PIT-tagged in the dorsal musculature by IfAÖ. Subsequent on-site biological maintenance of the Migromat® system was carried out by NUIG, following guidelines provided by IfAÖ. After stocking of Migromat®, the system was checked twice weekly for the first month, and once monthly thereafter, during both seasons, and any dead or infected (e.g. *Saprolegnia* sp.) eels were removed. At the end of each experiment phase, remaining eels were removed from the system.

3.3 Technical operation

Technical maintenance of the site and the Migromat® system was carried out by ESB and NUIG, in conjunction with IfAÖ and Floecksmühle Energietechnik GmbH. This involved general weekly maintainance of the site, as well as specific tasks such as cleaning of pumps, outlet grids etc. to prevent excess biofouling.

4. Killaloe silver eel fishery

The Killaloe eel weir (Fig. 3), which intercepts downstream migrating silver eels as part of the Irish Eel Management Plan trap and transport programme, acted as a proxy for a hydropower station. This allowed for evaluation of Migromat® alerts based on recorded catches at the weir. Killaloe eel weir (Cullen & McCarthy, 2000), the hydropower stations and the eel populations of the River Shannon are described in detail in previous publications (McCarthy & Cullen, 2000; Cullen & McCarthy, 2003; McCarthy *et al.,* 2008).

Figure 3. Killaloe eel weir, viewed from the western bank of the River Shannon.

Killaloe eel weir consists of an array of stow nets attached to a metal structure on the downstream side of a road bridge. In previous years, up to 34 nets were fished on the weir (Cullen & McCarthy, 2000). However, a compliment of 20-23 nets (at arches 2 to 8, Fig. 4) is more typical in recent seasons. Total catch consists of the cumulative catch of all nets and all net lifts on a particular night *i.e.* from net set (*c.* 16:00) to final net lift (*c.* 07:00). Multiple net lifts are required in times of high catches or high flow, to insure optimal condition of eels captured as part of the Irish Eel Management Plan. The fishing protocol at Killaloe during 2008/2009 generally consisted of nets being set at dusk, with one nightly lift (*c.* 22:00) and one morning lift (at dawn). During 2009/2010, an additional lift also took place, usually at 20:00.

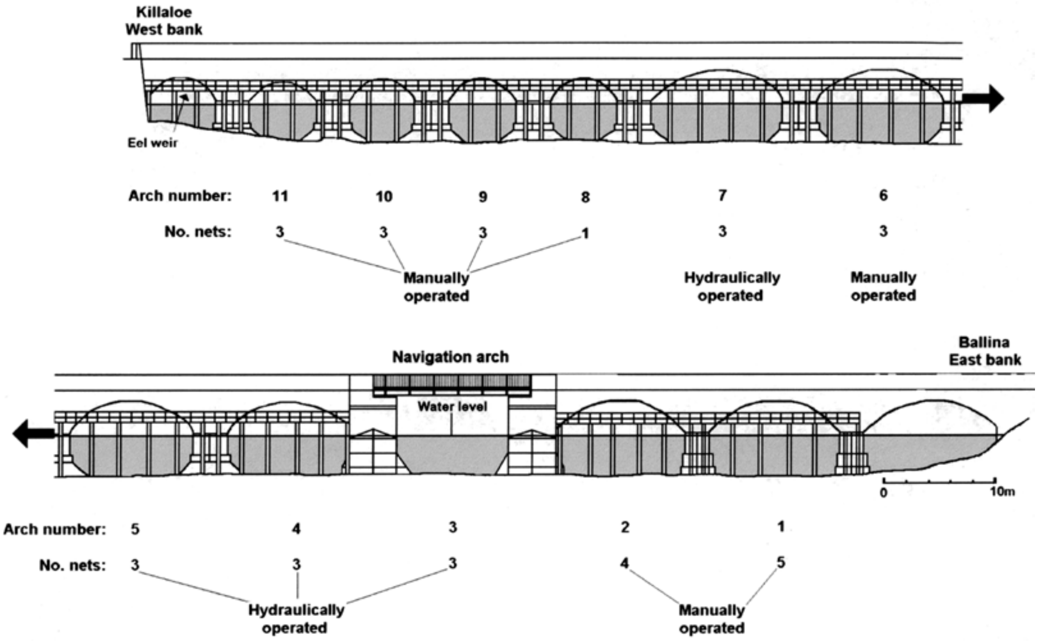

Figure 4. Schematic diagram of Killaloe eel weir (Cullen & McCarthy, 2000). The six index nets are positioned at arches 4 and 5.

5. Methods

5.1 Index nets

As the number of nets in operation at the weir varied, six adjacent hydraulically operated nets ('index nets'), positioned in the main flow of the river, where fished on all occasions, representing a constant and standard effort over space and time. All catch data presented (unless otherwise stated) relates to the index nets, which are indicated in Fig. 4 (arches 4 and 5). Catches from the index nets were weighed separately from the total catch.

5.2 Prevention of bias

Eel activity levels (*i.e.* PIT detections) in the Migromat® tanks were transmitted automatically to IfAÖ. This remote monitoring of the Migromat® enabled IfAÖ to declare the system operational when initial high activity levels (associated with handling and acclimatisation) had subsided, and detect any unusual activity patterns which would have required a site check.

When the activity threshold was reached in Migromat®, an eel migration alert was transmitted via email to IfAÖ and the French partners (EDF, ONEMA and HF). To prevent possible bias in fishing effort, the Irish partners (NUIG and ESB) were not informed of the alert for 3–5 days.

IfAÖ were only informed of Killaloe catches in the initial year: 30 days after they declared the Killaloe Migromat® operational on 31/10/2008 and at the end of the season. No catch data was given to IfAÖ in 2009/2010, to prevent adjustment of the Migromat® sensitivity during the experimental season.

5.3 Analytical methodology

Two alternative sets of analytical protocols were used in the evaluation of Migromat®:
1. Analysis of the index catch quantities which were signalled by Migromat® alerts (termed "absolute method").
2. Analysis of correctly and incorrectly–predicted migration events at specified catch levels, as well as migration events which were not signalled (termed "peak method"). The terminology used in this analysis is explained below:

- **Peak**: when index catch is greater than the defined threshold
- **Positive alert**: when alert corresponds to an index catch (*i.e.* peak) > the threshold
- **False alert**: when alert corresponds to an index catch < the threshold
- **Missed peak**: when an index catch > the threshold is not signalled by an alert.
- **Eels saved**: eels that would have been caught based on a positive alert

5.4 Alert interpretation

Standardised procedures were required in relation to the timing of Migromat® alerts, in order to simulate turbine shutdown under different circumstances. Therefore, three models of response to alerts were proposed for both analytical methods:

Instant model

If an alert is received during darkness, this model assumes immediate shutdown of the turbines, beginning when the alert is received, until dawn. If the alert is received during daylight, turbine shutdown begins at dusk, until dawn. Daylight times are based on sunlight data recorded at Parteen regulating weir, near the experiment site. During the study period, dusk generally occurred between 16:30-17:45 and dawn occurred between 07:30-08:30. Only a single alert is required to trigger turbine shutdown. Analysis of the instant model was performed using nightly net lift data, rather than the cumulative catch data as in the other models.

12:00 model

This model requires at least two Migromat® alerts to be received within 24 h of 12:00 on the day of net set: an initial alert and a confirmatory alert (together termed an "alarm event").

18:00 model

A variation of this model utilised an 18:00 deadline rather than 12:00, and operated as described above.

6. Results

6.1 Stocking, removal and mortality of eels in the Migromat®

2008/2009

During the first year of the project, the tagging and stocking of Migromat® eels took place on the 22/09/2008 and 23/09/2008. A total of 61 eels, were used for the experiment: 32 eels were placed in tank A and 29 in tank b. Eels were captured from four River Shannon sampling locations: Castleconnell and Lough Derg in the lower catchment; and Lough Ennel and Lough Sheelin in the upper catchment. The removal/mortality rates by location and capture method are summarised in Table 1. Maturation stage was estimated by visual examination of body colouration (Acou *et al.,* 2005).

Table 1. Summary results of observations on removal and mortality rates of Migromat® eels in 2008/2009.

Location	Capture method	n =	Maturation stage	Removal and mortality rate	
Castleconnell	Electrofishing	2	Yellow	0	0%
L. Derg	Fyke–net	15	Yellow	0	0%
L. Derg	Electrofishing	2	Yellow	1	50%
L. Ennel	River net	32	All silver	8	25%
L. Sheelin	Fyke–net	10	Mostly yellow	3	33.3%
Total		61		12	19.7%

During the 60–day Migromat® experimental period, a total of 4 eels died (6.6%). However, prior to the declaration by IFAÖ that the Migromat® was operational, 4 eels (6.6%) were removed from the tanks because of observed snout injuries with associated fungal (*Saprolegnia*) and possible secondary bacterial infections. The injuries to the eel heads may have been caused by net capture or by abrasion from escape attempts (*e.g.* by reaching up to water intake pipes or by rubbing against gratings near the outlet) during their reported high activity levels after their initial occupation of the tanks. Such problems were not noted subsequently and this may have been due to eels becoming adjusted to their Migromat® environment and declining water temperatures becoming less suited to *Saprolegnia* infection. After completion of the agreed 60–day continuous fishing period, a further 4 (6.6%) eels were removed dead from the tanks. The last mortality was reported on 08/04/2009, when the tanks were being drained and the Migromat® was being decommissioned after the season. The remaining 49 eels in the tanks were all in a healthy condition and were fully active. A summary of all eel removals from the Migromat® tanks is given in Table 2. Overall, the removal/mortality rate was 19.7% (12/61) and the numbers removed from tanks A and B were identical.

Table 2. Summary of eel removals from the Migromat® tanks (2008/2009).

Date	Tank	Alive / Dead
03/10/2008	A	Alive
	A	Alive
	A	Alive
14/10/2008	A	Alive
13/11/2008	B	Dead
	B	Dead
09/12/2008	B	Dead
	B	Dead
06/1/2009	B	Dead
	B	Dead
23/3/2009	A	Dead
08/4/2009	A	Dead

During removal of the eels it was possible to locate 3 PIT tags in the sediment in the drained tanks. As examination of the 49 removed live eels showed that 5 eels lacked PIT tags (1 from tank A and 4 from tank B), it is assumed that the other two tags had been washed out during the lowering of the water levels and draining of the tanks. By noting the PIT tag identities of the eels removed, it was possible to determine the sampling location and sizes of the eels involved. These included two eels from Lough Derg (tagged on 22/09/2008) and three from Lough Ennel (tagged on 23/09/2008). However, no clear pattern was noted in that a range of eel sizes (47–76.5cm) were involved (*i.e.* no size bias) and both Lough Derg yellow and Lough Ennel silver eels were involved (*i.e.* no location or sampling date bias).

2009/2010

Capture of eels for the 2009/2010 phase of the experiment took place in lower Lough Derg between 31/07/2009 and 04/08/2009, resulting in a combined catch of 331 eels. On 06/08/2009, 58 eels, deemed to be of sufficient size (*i.e.* >500 mm), were selected for stocking of the tanks. All eels were anaesthetised, measured to the nearest 5 mm and PIT tagged (by IfAÖ). Selected eels were also examined morphometrically (weight to nearest 1 g; fin length to 0.1 mm; eye diameter to 0.1 mm) by NUIG before being placed in a recovery bin and subsequently in the Migromat® tanks. 31 eels were placed in tank A and 27 eels were placed in tank B.

As all eels selected were greater than 500 mm, all were classified as female. Eye index (Pankhurst, 1982) for sub-sampled eels (n = 33) ranged from 0.9-8.2 (mean=3.8). Only one eel had eye index >6.5, and all eels except two (6.1%) were classified as resident, according to Durif *et al.,* (2005). Fin index (Durif *et al.,* 2005) for sub-sampled eels (n=39) ranged from 3.4–5.5 (mean=4.5) *i.e.* 30.8% resident and 69.2% pre-migrant. Visual examination (n=59) of body colouration (Acou *et al.*, 2005) indicated that five eels (8.5%) were 'silvering'. Based on eye and fin index parameters (n=32), 6.25% of eels were classified as pre-migrant, and based on all three parameters (n=32), 3.13% were classified as silvering/pre-migrant.

During the operational period of the Migromat®, three eels were removed from tank A: one live eel with *Saprolegnia* infection noted around the PIT tag insertion wound and two badly decayed dead eels. A fourth eel, also badly decayed, was removed from tank B when the tanks were being emptied at the end of the season. Thus, the overall removal/mortality for the season was 6.9% (4/58). A summary of all eel removals from the Migromat® tanks is given in Table 3.

Table 3. Summary of observations on removal and mortality rates for Migromat® eels in 2009/2010.

Date	**Tank**	**Alive / Dead**	**Notes**
28/08/09	A	Alive	Fungus
06/10/09	A	Dead	Decayed
06/10/09	A	Dead	Decayed
25/03/10	B	Dead	Decayed

6.2 Eel catch data

Index catches were shown to be highly significantly correlated (Spearman, r_S) with corresponding total catches [(2008/2009: r_S=0.982, P<0.001) (2009/2010: r_S=0.992, P<0.001) (pooled: r_S=0.989, P<0.001)]. This is illustrated by the linear regression lines presented in Fig. 5. The total and index catches recorded at Killaloe in 2008/2009 were 10,472 kg and 4,707 kg, and in 2009/2010 were 12,022 kg and 6,694 kg. In 2008/2009, 2,633 kg (55.9%) of the index catch was made prior to the Migromat® being declared operational on 31/10/2008, indicating that significant silver eel migration had already taken place. In 2009/2010, the earlier start date of the evaluation ensured that main eel migration at Killaloe took place subsequent to the Migromat® being declared operational (on 16/08/2009). Index catches for the entire silver eel fishing season in 2008/2009 and 2009/2010 are illustrated in Fig. 6.

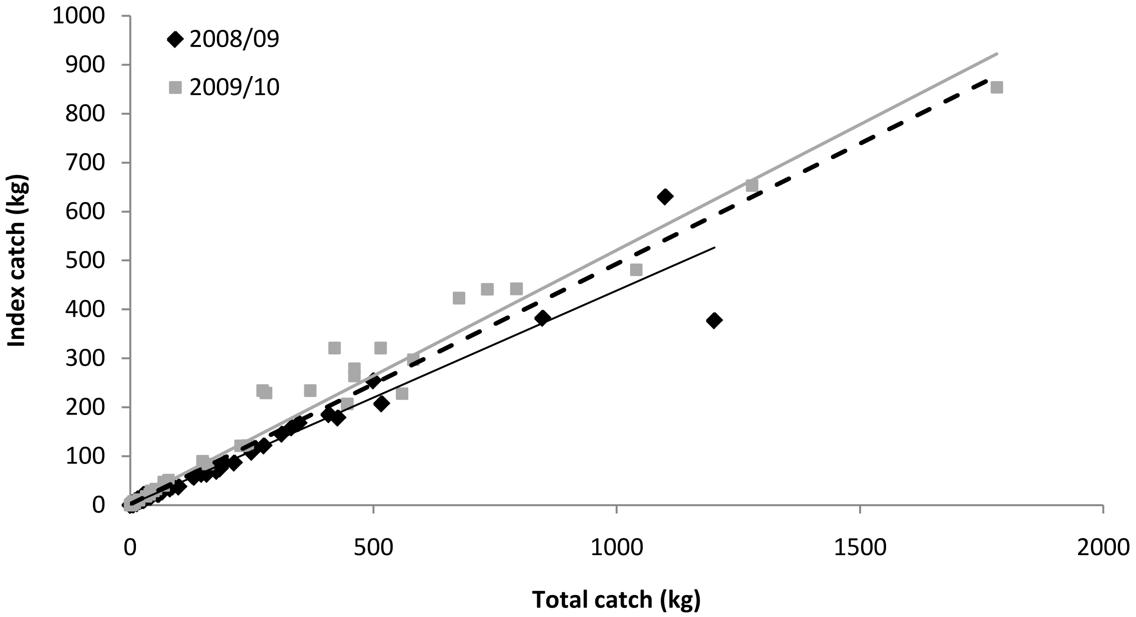

Figure 5. Relationship between the nightly total and index catches at Killaloe for 2008/2009, 2009/2010, and pooled (indicated by dashed line).

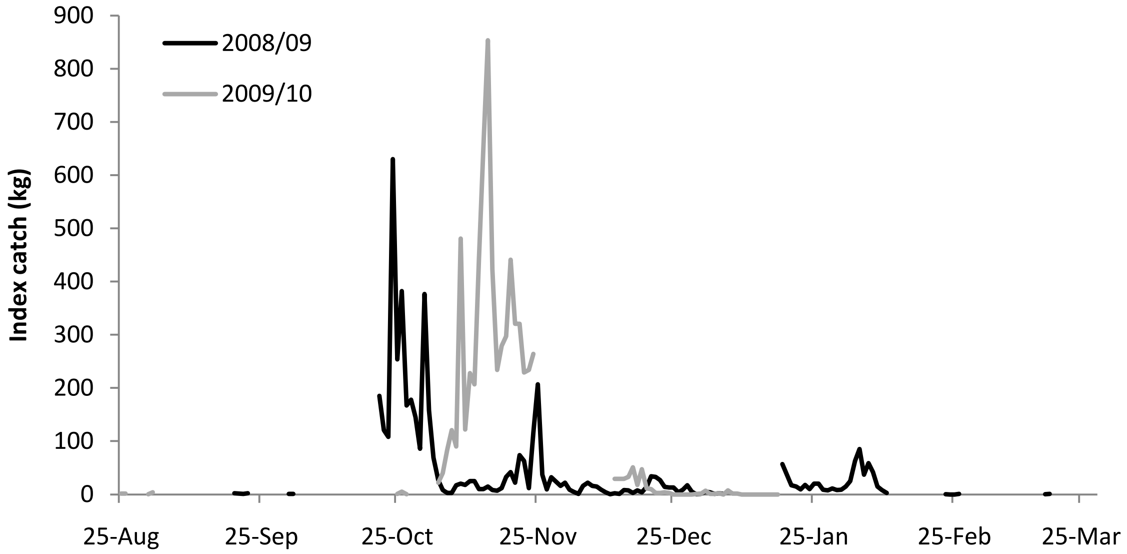

Figure 6. Index net catches recorded at Killaloe eel weir during the entire fishing seasons in 2008/2009 and 2009/2010.

Due to extreme discharge and flooding of the River Shannon during winter 2009, operation of the weir ceased on 24/11/2009 for health and safety reasons. Therefore, no catch records were available from Killaloe for the 17–day period from 25/11/2009–11/12/2009. However, novel counting protocols using a sonar camera (DIDSON) allowed for the estimation of the eel run at Killaloe. Prior to the fishery closure, the DIDSON camera was positioned on the eel weir to observe specific net openings, in order to establish a DIDSON count to catch relationship. Index catch on these occasions ranged from 0–351 kg (mean 131.5 kg) and a highly significant correlation (r_S=0.851, P<0.001) was noted between DIDSON observations and the catch of the observed Killaloe eel weir nets.

During the closure period, the DIDSON camera was deployed adjacent to the Migromat® site, 700 m upstream of the weir, as use of the camera on the weir was not possible for health and safety reasons. Eel counts were made on six nights (*i.e.* every 2–3 nights) during the closure period (Fig. 8). After fishing resumed on 11/12/2009, upstream DIDSON observations were related to the corresponding index catches (n=3). Additional observations were conducted during the 2010/2011 season (n=7) and the relationship is illustrated in Fig. 7. Index catches were adjusted to take account of sex ratio and mean size differences.

Using the regression equation (Index catch = 0.61 * DIDSON counts – 1.05; R^2=0.759 P<0.001), index catches for the six nights of DIDSON observations during the fishery closure period were estimated, and were interpolated to estimate index catch throughout the fishery closure period (Fig. 8). The cumulative index catch was estimated to have been 1544 kg if fishing had not ceased.

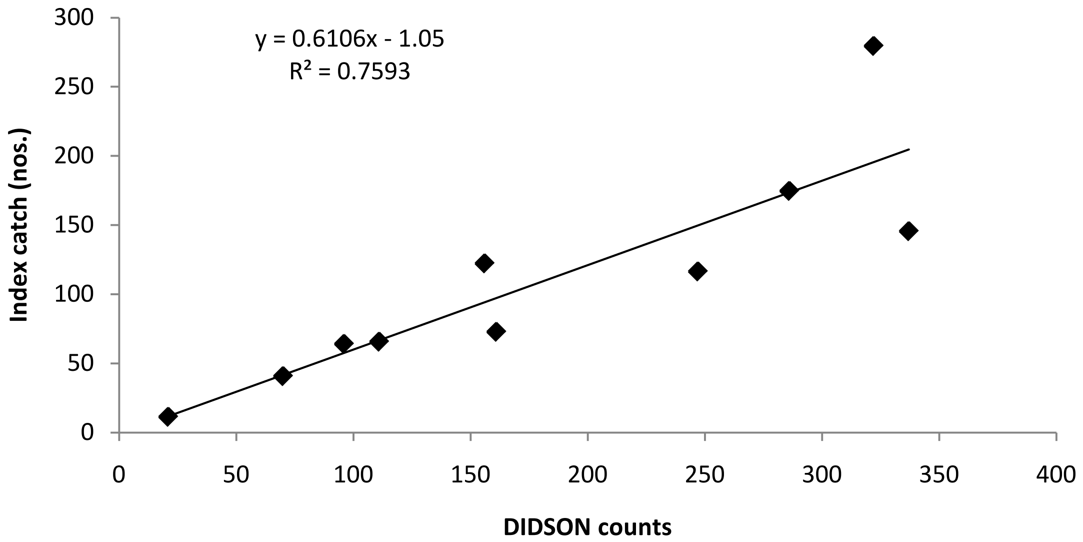

Figure 7. DIDSON observations upstream of the eel weir (nos. of individuals) and Killaloe catch (nos. of individuals).

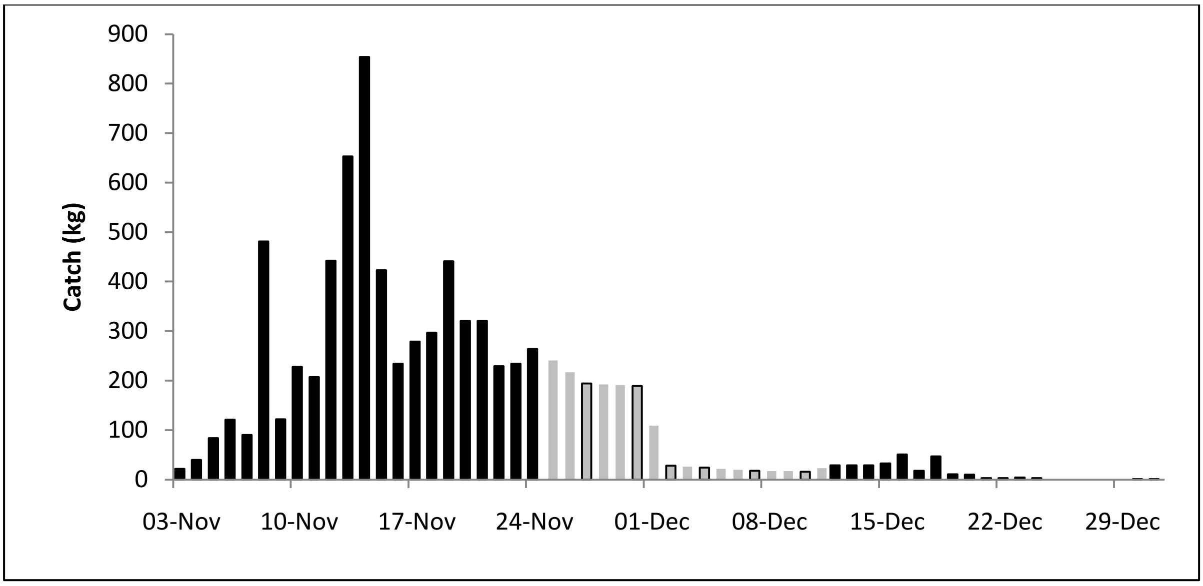

Figure 8. Killaloe catch (black) with DIDSON estimated catch (grey). Black outlined bars indicate the nights when DIDSON observations were made.

Both seasons were different in terms of the temporal distribution of catches. In 2008/2009, a total of 115 nights were fished. The main migration period started early, and a smaller migration took place late in the season. In 2009/2010, test fishing took place earlier (25/08/2009–27/10/2009) but the main migration period (03/11/2009–24/11/2009) started later than 2008/2009. The closure of the fishery in 2009/2010 complicated interpretation of the data. However, no late season migration (as in 2008/2009) was detected. Also, daily catches were generally higher in 2009/2010 (probably due to the reduced silver eel fishing effort upstream, and the cessation of the summer yellow eel fishery from 2008 onwards). This enabled a higher total catch to be made in 2009/2010, despite less nights being fished (68 nights). Occasions when the daily catch exceeded 50, 100, 200 and 400 kg, as well as the maximum daily catch, are summarised in Table 4, illustrating the difference in composition of catches between the two years.

Table 4. Summary of daily catches in 2008/2009 (entire season and 98–day Migromat® operational period) and 2009/2010 (entire season and continuous fishing period).

Catch	**2008/09**		**2009/10**	
	Entire season	*98–day Migromat® operational period (31/10/08–28/03/09)*	*Entire season*	*Continuous fishing period (03/11/09–17/01/10)*
> 50 kg	17	10	21	21
> 100 kg	13	3	18	18
> 200 kg	5	1	15	15
> 400 kg	1	0	6	6
Max	630 kg	207 kg	854 kg	854 kg

6.3 Efficiency of Migromat®

2008/2009

The Migromat® was declared operational by IfAÖ on 31/10/2008 and only catch data subsequent to this were analysed. The fishing season was divided into the 60–day continuous fishing period (31/10/2008–30/12/2008) and 98–day Migromat® operational period (31/10/2008-28/03/2009). The latter was not a continuous fishing period as not every alert was verified by fishing.

Using the protocols outlined above ("absolute" and "peak" methods), the following Migromat® efficiency was calculated for 2008/2009 (instant model, 12:00 model and 18:00 model) (Table 5).

Table 5. Summary of Migromat® alerts (instant, 12:00 and 18:00 models) and corresponding catches analysed using the absolute protocol during the 60–day continuous and 98–day Migromat® operational fishing periods.

	Date	Time	Instant model	12:00 model		18:00 model	
				Alarm Event	Catch	Alarm Event	Catch
↑	24/11/08	04:03	207 kg	1.	207 kg	1.	207 kg
	24/11/08	06:03					
60–day	24/12/08	06:03	13 kg	*Unconfirmed*	–	*Unconfirmed*	–
	25/12/08	13:03	4 kg	2.	9 kg	2.	9 kg
↓	26/12/08	06:03	9 kg				
	17/01/08	16:03	57 kg	3.	37 kg	3.	37 kg
	18/01/09	06:03	37 kg				
	05/02/09	16:03	59 kg	4.	42 kg	4.	42 kg
	06/02/09	07:04	42 kg				
	22/02/09	10:03	0.5 kg	5.	0.5 kg	5.	0.5 kg
	22/02/09	11:04					
98–day	23/02/09	20:04	0 kg	6.	0 kg	6.	0 kg
	24/02/09	07:03	0 kg				
	05/03/09	10:04	1 kg	7.	1 kg	7.	1 kg
	05/03/09	11:03					
	15/03/09	00:04	No fishing	8.	0.5 kg	8.	0.5 kg
	16/03/09	07:03	0.5 kg				
	17/03/09	15:03	1 kg	9.	No fishing	9.	No fishing
↓	18/03/09	07:04	No fishing				
	02/04/09	15:03	No fishing	10.	No fishing	10.	No fishing
	03/04/09	06:04	No fishing				
TOTAL (continuous period)			233 kg	216 kg		216 kg	
TOTAL (98–day Migromat® operational period)			431 kg	297 kg		297 kg	

During the 60–day continuous fishing period, the cumulative catch was 1,456 kg. All alerts were fished. The instant model resulted in a catch of 233 kg (16%). The 12:00 model resulted in a catch of 216 kg (14.8%), as did the 18:00 model.

The cumulative catch at Killaloe during the 98–day Migromat® operational period was 2,074 kg. Based on the instant model, 431 kg of eels (20.8%) were captured. A total of 297 kg (14.3%) of eels were captured using the 12:00 and 18:00 models. For both models (12:00 and 18:00), the alert on 24/12/2008 at 06:03 was excluded as a confirmatory alert was not received. Alarm events 9 and 10 were excluded as no corresponding catch data was available.

The peak analysis methodology was also used to evaluate the predictive capacity of Migromat®. This involved assessing the numbers of migration peaks signalled by alerts using the models described above (*i.e.* instant, 12:00 and 18:00). In Tables 6–8, the results are presented by reference to different thresholds (*i.e.* catches exceeding 25, 50, 100 and 200 kg).

Table 6. Summary of Migromat® efficiency during the 98–day Migromat® operational period (instant model).

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved
> 25kg	16	5	9	11	402 kg
> 50 kg	10	3	11	7	323 kg
> 100 kg	3	1	13	2	207 kg
> 200 kg	1	1	13	0	207 kg

Table 7. Summary of Migromat® efficiency during the 98–day Migromat® operational period (12:00 model).

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved
> 25kg	16	3	5	13	286 kg
> 50 kg	10	1	7	9	207 kg
> 100 kg	3	1	7	2	207 kg
> 200 kg	1	1	7	0	207 kg

Table 8. Summary of Migromat® efficiency during the 98–day Migromat® operational period (18:00 model).

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved
> 25kg	16	3	5	13	286 kg
> 50 kg	10	1	7	9	207 kg
> 100 kg	3	1	7	2	207 kg
> 200 kg	1	1	7	0	207 kg

2009/2010

The Killaloe catch during 2009/2010 is summarised in Table 9. The Migromat® was declared operational on 16/08/2009. The pre-continuous period refers to 25/08/2009–27/10/2009, while the continuous period extends from 02/11/2009–17/01/2010. The 'catch only' column excludes the 17–day fishery closure period, whereas the 'catch + DIDSON' column includes estimated catches during this period.

Table 9. Summary of Killaloe catch during each component of the 2009/10 season.

	Pre–continuous	**Continuous**	**Entire season**
Catch only	13.5 kg	6680.5 kg	6694 kg
Catch + DIDSON	13.5 kg	8224.5 kg	8238 kg

Table 10. Summary of Migromat® alerts (instant, 12:00 and 18:00 model) and corresponding catches analysed using the absolute protocol during the pre–continuous fishing period in 2009/2010.

Date	**Time**	**Instant model**	**12:00 model**		**18:00 model**	
			Alarm Event	**Catch**	**Alarm Event**	**Catch**
24/08/09	20:04	No fishing	1.		1.	
25/08/09	06:03	5 eels		5 eels		5 eels
29/08/09	17:04	No fishing	2.		2.	
30/08/09	06:03			3 eels		3 eels
30/08/09	18:03	3 eels	3.		3.	
31/08/09	06:03	13 eels		13 eels		13 eels
07/10/09	00:04	No fishing	4.		4.	
07/10/09	06:03	No fishing		No fishing		No fishing
15/10/09	18:03	No fishing	5.		5.	
16/10/09	06:03	No fishing		No fishing		No fishing
16/10/09	14:04	No fishing	6.		6.	
17/10/09	06:03	0 eels		0 eels		0 eels
27/10/10	08:03		7.		7.	
27/10/10	09:03	1 eel		1 eel		1 eel
TOTAL		13.5 kg		13.5 kg		13.5 kg

During the pre–continuous fishing period, there were 14 individual alerts and 7 alarm events (Table 10). Alarm events 4 and 5 were omitted from analysis as corresponding catch records were not available. Total catch based on Migromat® alarm events (n=5) using the instant model was 13.5 kg. A number of alerts were omitted due to lack of corresponding fishing. The catch is the same using the 12:00 and 18:00 models.

Table 11. Summary of Migromat® alerts (instant, 12:00 and 18:00 model) and corresponding catches analysed using the absolute protocol during the continuous fishing period. * denotes DIDSON–estimated catches.

Date	**Time**	**Instant model**	**12:00 model**		**18:00 model**	
			Alarm Event	**Catch**	**Alarm Event**	**Catch**
13/11/09	22:03	309 kg	1.		1.	
14/11/09	06:03	423 kg		423 kg		423 kg
19/11/09	11:03		Unconfirmed	–	2.	
19/11/09	18:03	321 kg	2.			321 kg
20/11/09	06:03	321 kg		321 kg	3.	321 kg
21/11/09	09:03		3.		4.	
21/11/09	10:03			229 kg		229 kg
21/11/09	21:03	229 kg	4.		5.	
22/11/09	06:03	234 kg		234 kg		234 kg
23/11/09	23:03	107 kg	5.		6.	
24/11/09	06:03	241 kg*		241 kg*		241 kg*
27/11/09	06:03		6.		7.	
27/11/09	07:03	192 kg*		192 kg*		192 kg*
12/01/09	05:03		7		8.	
12/01/09	06:03	0 kg		0kg		0 kg
TOTAL (catch only)		1944 kg		1207 kg		1528 kg
TOTAL (catch + DIDSON)		2377 kg		1640 kg		1961 kg

For the continuous fishing period, there were 15 alerts (Table 11). The total catch was 6,680.5 kg, or 8,224.5 kg including the estimated catch during the fishery closure (catch + DIDSON). Based on the instant model, 1,944 kg was captured (29.1% of catch only), or 2,377 kg (28.9% of catch + DIDSON). The 12:00 model resulted in the capture of 1,207 kg (18.1%) or 1,640 kg (19.9%). The alarm on 19/11/09 at 11:03 was excluded from analysis as a confirmatory alert was not received. Finally, the 18:00 model would have enabled the capture of 1,528 kg (22.9%), or 1,961 kg (23.8%).

Alternatively, using the peak analytical method, the results are presented below by reference to different thresholds (*i.e.* catches exceeding 50, 100, 200 and 400 kg) for catch only and catch + DIDSON scenarios using the instant model (Tables 12 and 13), 12:00 model (Tables 14 and 15) and 18:00 model (Tables 16 and 17).

Table 12. Summary of Migromat® efficiency during the continuous fishing period (catch only) using the instant model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	21	7	1	14	1,944 kg
> 100 kg	18	7	1	11	1,944 kg
> 200 kg	15	6	2	9	1,837 kg
> 400 kg	6	1	7	5	423 kg

Table 13. Summary of Migromat® efficiency during the continuous fishing period (catch + DIDSON) using the instant model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	28	9	1	19	2,377 kg
> 100 kg	24	9	1	15	2,377 kg
> 200 kg	16	7	3	9	2,078 kg
> 400 kg	6	1	9	5	423 kg

Table 14. Summary of Migromat® efficiency during the continuous fishing period (catch only) using the 12:00 model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	21	4	1	17	1,207 kg
> 100 kg	18	4	1	14	1,207 kg
> 200 kg	15	4	1	11	1,207 kg
> 400 kg	6	1	4	5	423 kg

Table 15. Summary of Migromat® efficiency during the continuous fishing period (catch + DIDSON) using the 12:00 model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	28	6	1	22	1,640 kg
> 100 kg	24	6	1	18	1,640 kg
> 200 kg	16	5	2	11	1,448 kg
> 400 kg	6	1	6	5	423 kg

Table 16. Summary of Migromat® efficiency during the continuous fishing period (catch only) using the 18:00 model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	21	5	1	16	1,528 kg
> 100 kg	18	5	1	16	1,528 kg
> 200 kg	15	5	1	10	1,528 kg
> 400 kg	6	1	5	5	423 kg

Table 17. Summary of Migromat® efficiency during the continuous fishing period (catch + DIDSON) using the 18:00 model.

Peak criteria	No. of peaks	Positive alerts	False alerts	Missed peaks	Eels saved (positive alerts only)
> 50 kg	28	7	1	21	1,961 kg
> 100 kg	24	7	1	21	1,961 kg
> 200 kg	16	6	2	10	1,769 kg
> 400 kg	6	1	7	5	423 kg

6.4 Turbine shutdown

The overall objective of the 2008–2010 Killaloe project was to evaluate the predictive potential of the Migromat® system to enable hydropower operators to mitigate for the adverse effects of turbine passage on silver eels. If effective, this could serve as an alternative to existing mitigation measures, such as silver eel trap and transport, and the use of mechanical or behavioural barriers. When a migration event is signalled by Migromat®, turbine shutdown could ensue, and downstream passage of eels could be facilitated via an alternative route (*e.g.* spillways, sluices, culverts). The potential loss of hydropower generation (in hours) due to Migromat® alerts, in relation to total generation during the migration season (assuming 24 hour generation), is outlined below. For the instant model, turbine shutdown is assumed to take place at dusk subsequent to a daytime alert, or immediately in the case of a night time alert. For the 12:00 model, the number of hours the turbines are assumed to be stopped corresponds to the dusk to dawn period. In the case of the 18:00 model the turbine shutdown period is either from dusk to dawn or else 18:00 to dawn, depending on the alert timing.

2008/2009

In 2008/2009, 24 $h.d^{-1}$ generation during the 60–day continuous fishing period would have resulted in a maximum of 1,440 generation hours (g hrs). Migromat® alerts received during this period and interpreted using each model would have resulted in a loss of generation of: instant model = 64 hrs (4.4%); 12:00 model = 32 hrs (2.2%);

18:00 model = 32 hrs (2.2%). The number of consecutive nights of turbine shutdown according to each model is presented in Table 18.

Table 18. Consecutive nights of turbine shutdown according to each model.

Instant	**12:00**	**18:00**
1 x 1 night 1 x 3 nights	2 x 1 night	2 x 1 night

2009/2010

In 2009/2010, 24 h.d^{-1} generation for the main fishing period (02/11/2009–17/01/2009), would have resulted in a total of 1,464 g hrs (or 1,848 g hrs including the 17–day non–fishing period). Based on the instant model, turbine shutdown would have occurred for 109 hrs (fishing nights only) or 139 hrs (fishing nights + DIDSON nights), representing 7.4% or 7.5% of total g hrs respectively. For the 12:00 model, turbine shutdown would have occurred for 75 hrs or 105 hrs, representing 5.1% or 5.7% of total g hrs respectively. For the 18:00 model, loss of generation would have been 94 hrs or 126 hrs, representing 6.4% or 6.8% of total g hrs respectively. The number of consecutive nights of turbine shutdown according to each model is presented in Table 19.

Table 19. Consecutive nights of turbine shutdown according to each model.

Instant	**12:00**	**18:00**
2 x 1 night 1 x 2 nights 1 x 6 nights	3 x 1 night 1 x 4 nights	3 x 1 night 1 x 5 nights

6.5 Late detection of peaks

The analyses, undertaken using the results of the Killaloe 2008–2010 Migromat® evaluation study, highlighted the fact that alarms frequently coincided with a sustained migration period, rather than signalling individual peaks (Fig. 8 and 9). This absence of pre–migration prediction meant that the predictive value of the system was more limited than expected. As can be seen below, Migromat® alarms were closely related to increasing discharge (Fig. 9). A possible influence of lunar phase on Migromat® eel activity is also suggested by the data, especially during the 2008/2009 season (Fig. 8).

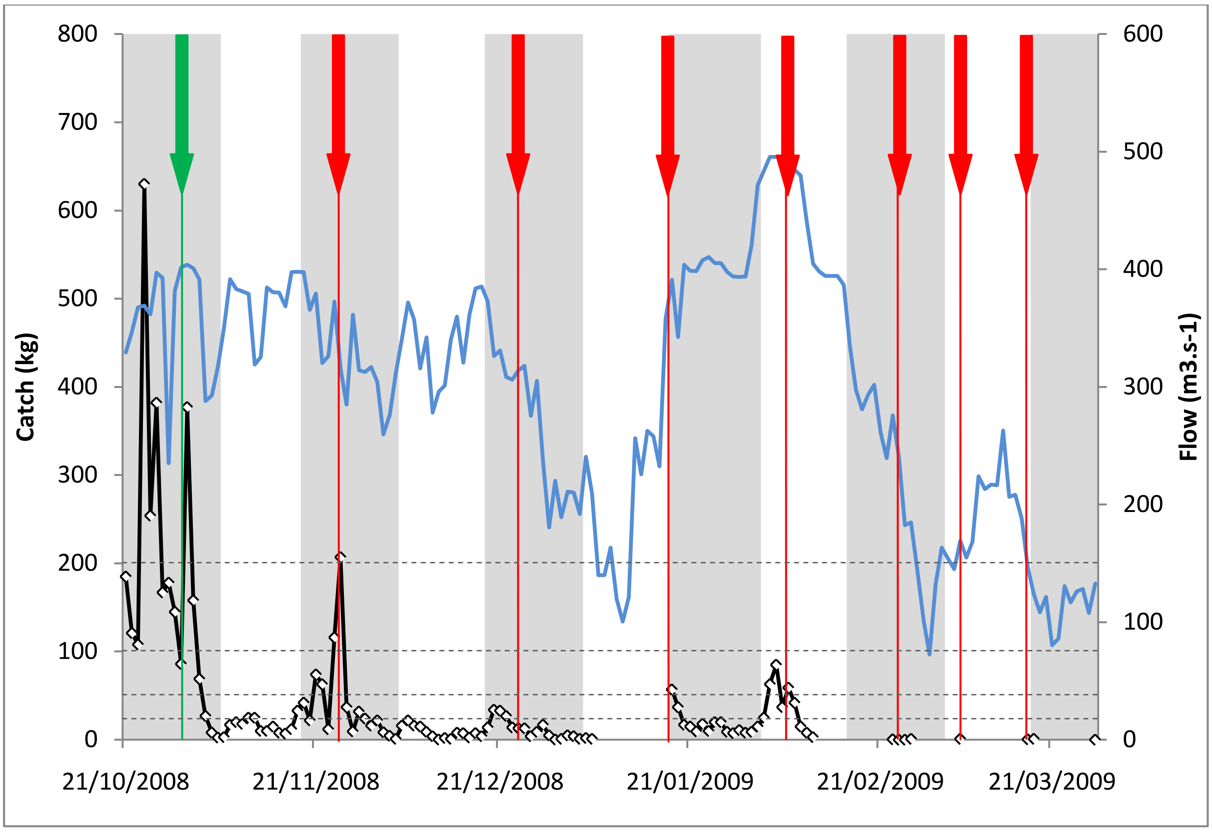

Figure 8. Killaloe catch and Migromat® alerts in 2008/2009. Green arrow indicates when Migromat® was declared operational, red arrows indicate Migromat® alerts, black line is Killaloe catch, blue line is discharge, grey areas are the lunar dark periods (*i.e.* last quarter to first quarter) and the dashed lines indicate the 25, 50, 100, and 200 kg thresholds.

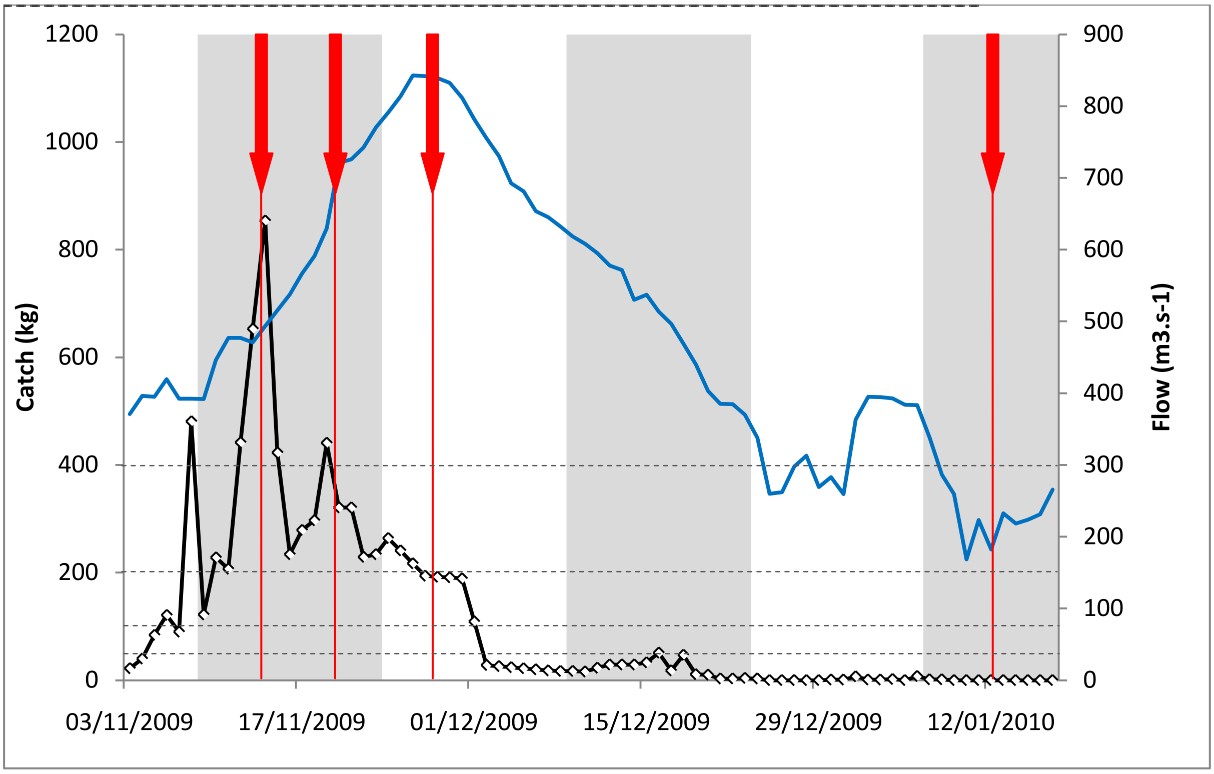

Figure 9. Killaloe catch and Migromat® alarms in 2000/2010. Migromat® was declared operational on 16/08/2009. Red arrows indicate Migromat® alerts, black line is Killaloe catch, blue line is discharge, grey areas are the lunar dark periods (*i.e.* last quarter to first quarter) and the dashed lines indicate the 50, 100, 200 and 400 kg thresholds.

Graphs detailing Killaloe catch (2008/09 and 2009/10) in relation to Migromat® alarms/turbine shutdown for each model (instant, 12:00 and 18:00) are included in Appendix 2.

6.6 Alternative prediction

For comparison of alternative predictive methods with Migromat®, the main eel migration period in 2009/2010 (03/11/2009–17/01/2010 including fishery closure period; 76–days in total), was selected. A summary of the alternative results are given below:

Lunar dark

A simple prediction model involving turbine shutdown on 3 d per lunar dark (*i.e.* new moon ± 1 d) over three lunar cycles (Nov, Dec, and Jan; 9 d total) would have saved 1,038 kg (12.9%) of the total index catch (8,081.5kg).

Random selection

Based on the 12:00 model, seven Migromat® alarm events were signalled during the 76 night eel migration period. For random selection analyses, each consecutive night was numbered from 1–76. Using a random number generator, seven numbers were selected and the catches were treated as a cumulative quantity of eels saved. This analysis was replicated ten times. The results ranged from 336 kg–1,788 kg (mean = 1,015 kg). This equates to 12.6% of the total index catch during this period. However, the replicated results ranged from 4%–22.1%.

6.7 Fisherman predictions

During both years, the Killaloe eel weir fishing crew were asked each day, prior to net setting, to provide an estimate of the catch they anticipated making on that night. They had knowledge of the preceding night's catches and of the prevailing environmental conditions. Likewise, they had experience gained in previous years that assisted them in understanding the patterns of eel migration at the site. For the analysis of their predicted catches in 2009/10, the 17-day fishery closure period was excluded. Therefore, the cumulative index catch for the period 02/11/2009 to 17/01/2010 was 6,680.5 kg. Four alternative calculations, of potential reductions in eel mortality, using these predictions, are considered below:

Predictions on Migromat® alarm event nights

During the defined period, fishing corresponding to Migromat® alarms events yielded 1,944 kg (instant), 1,207 kg (12:00) or 1,528 kg (18:00). This equates to 29.1%, 18.1% or 19.9% of the total catch, respectively. Fishermen's predictions on these nights indicated that they expected a catch of 1,261kg to be made (18.9% of the total catch).

Nights with predicted catches above 200 kg

The eel weir fishing crew predicted the index catch would be greater than 200 kg on 12 occasions, with an accuracy of 91.7% (*i.e.* correct 11 out of 12). Fishing on these 12 nights only would have yielded 4,397 kg (65.8% of total index catch). Loss of generation would have been 10.7% and the number of consecutive nights of turbine shutdown would have been: 1 x 1 night; 1 x 2 nights; 1 x 3 nights; 1 x 6 nights.

Nights with predicted catches above 400 kg

The eel weir fishing crew predicted the index catch would be greater than 400 kg on 4 occasions, with an accuracy of 50%. Fishing on these 4 nights only would have yielded 1,850 kg (27.7% of total index catch). Loss of generation would have been 3.6% and the number of consecutive nights of turbine shutdown would have been: 2 x 1 night; 1 x 2 nights.

7 nights with highest predicted catches

The total predicted index catch was 3,085 kg. Fishing on the nights with the 7 highest predictions, would have resulted in 2,891 kg (43.7% of total index catch). Loss of generation would have been 6.2% and the number of consecutive nights of turbine shutdown would have been: 1 x 3 nights; 1 x 4 nights.

6.8 Actual catch

By examination of the recorded daily index catches it was possible to identify the best possible combination of nights and therefore indicate the maximal quantities of eels that might be saved if a 100% accuracy of prediction had been possible. The fishery closure period is included in this analysis (*i.e.* 76 nights). Some results that illustrate this approach are given below, and the cumulative catch (in %), ranked in decreasing size, is given in Fig. 10.

Best 7 nights

This would have yielded 3,615 kg or 44% of total index catch. Loss of generation would have been 4.9% and the number of consecutive nights of turbine shutdown would have been: 1 x 1 night; 1 x 2 nights; 1 x 3 nights.

Best 9 nights

This would have yielded 4,233 kg or 52.4% of total index catch. Loss of generation would have been 6.3% and the number of consecutive nights of turbine shutdown would have been: 1 x 1 night; 2 x 4 nights.

Best 15 nights

This would have yielded 5,714 kg or 69.5% of total index catch. Loss of generation would have been 10.6% and the number of consecutive nights of turbine shutdown would have been: 1 x 1 night; 2 x 4 nights; 1 x 6 nights.

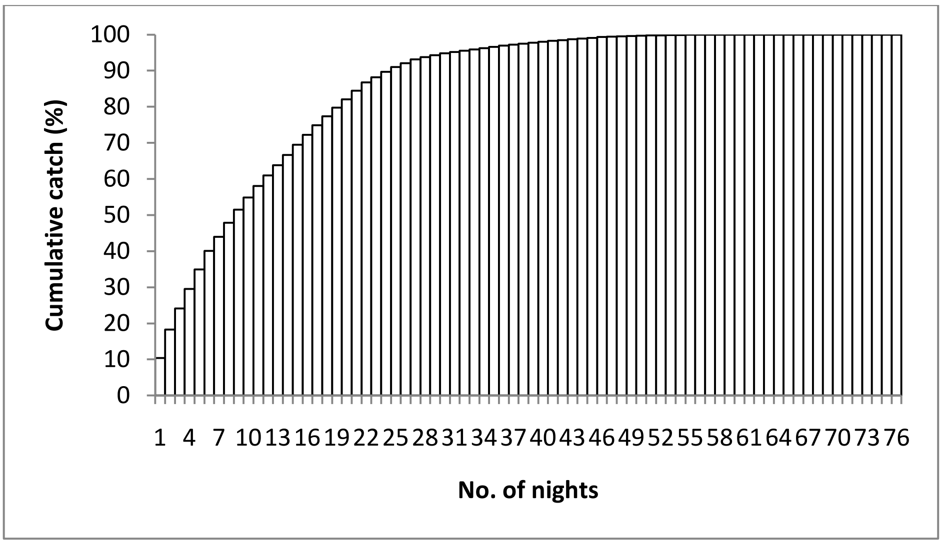

Figure 10. Cumulative % Killaloe catch (2009/2010) ranked by decreasing size.

7. Discussion

The project work programme involved important differences between actions and communication protocols for the 2008/2009 and 2009/2010 experimental seasons. The initial year was intended to allow for calibration and adjustments to be made by IfAÖ to the Migromat® system, taking account of Killaloe eel behaviour patterns and other local factors. Daily eel catch data were provided to IfAÖ 30 days after they declared the Killaloe Migromat® operational on 31/10/2008. Likewise, information on eel mortalities/removals was also provided. An interim review of the operation and the progress of the Migromat® evaluation took place during a project partners meeting, attended by IfAÖ, in France on 02/12/2008. A subsequent end of year one meeting took place in Limerick on 17/06/2009.

In 2008/2009, the late start to the Migromat® operational period meant that significant silver eel migration had taken place at Killaloe prior to the agreed 60–day fishing period used in the system evaluation. However, the technical evaluation of the system confirmed that in terms of both biological (eel condition) and engineering (mechanical, electrical, software systems) performance, Migromat® was robust and that very few issues requiring maintenance activity arose. Likewise, communications between participants in the project were effective.

In 2009/2010, Migromat® was operational much earlier in the season (16/08/2009). As in the initial year, no significant maintenance problems arose. The silver eel migration season on the River Shannon was unusual because of extreme weather conditions and flooding. This required adaptation of the project work programme due to the 17–day closure of the Killaloe eel weir fishery, on health and safety grounds. However, the evaluation of the Migromat® system was successfully undertaken, using novel DIDSON count protocols. The results were reviewed by telephone conferencing and at a project partners meeting in Tuilieres, France, on 26–27/04/2010.

This project aimed to establish if Migromat® could potentially be used in support of mitigation measures at a hydropower installation, which was adversely affecting downstream migrating eels. Turbine shutdown during long periods (*e.g.* entire autumn migration season) would have serious economic impacts for electricity producers. Therefore, accurate prediction (*e.g.* using Migromat®) of silver eel migration events would enable fisheries managers and hydropower operators to implement short, specific periods of turbine shutdown and controlled spillage. However, the evaluation of the Migromat® system undertaken at Killaloe did not, contrary to previously published conclusions (Bruijs *et al.,* 2009), suggest that the technology was likely to be cost–effective in this regard. The overall conclusion reached was that Migromat® was a relatively poor predictor of eel catches at the Killaloe eel weir. Therefore, it would be of very limited value as a biomonitoring tool in respect of a hydropower station that might theoretically be located at that site and would be unlikely to satisfy the requirements of Ireland's National Eel Management Plan, which specifies major eel conservation actions. The quantities of eels that could potentially have been saved by turbine shutdown on the basis of Migromat® alerts, in either 2008/2009 (14.3–20.8% of total catch) or 2009/2010 (18.1–29.1% of total catch), were relatively small. This low efficiency is most likely due to the fact that alerts were generally received *during* the main migration peak, rather that *before* it (*i.e.* lack of pre–migration prediction), and hence a significant proportion of the silver eels migrated undetected prior to the alerts. However, some degree of Migromats® predictive capacity is evident by the fact that 18.1–29.1% of the total catch was obtained with only 5.1–7.4% loss of generation.

A variety of alarm interpretations were used in the Killaloe Migromat® evaluation project. However, the 12:00 model seems to most realistically simulate the conditions and constraints under which a large hydropower station would have to operate. Application of this model in respect of the main fishing period in 2009/2010 (including the fishery closure) indicated that 19.6% of the annual migratory silver eel population would have been saved by turbine shutdown in response to Migromat® alarms (Table 11), and loss of generation would have amounted to 5.7% of the total season production.

However, significant quantities of eels could also have been saved by turbine shutdown using simpler management options. If hydropower generation ceased during 3 selected nights per lunar dark (new moon ± 1 d; 9 nights total) over the main eel migration season, it was concluded that 12.9% of the run would have been saved. Likewise, random selections of nights for turbine shutdown often produced results (10 random selections, range=4%–22.1%, mean=12.6%) comparable with those obtained using Migromat® alerts.

Predictions made by the Killaloe eel weir fishing crew, in which they provided nightly catch forecasts in advance, are generally superior to the estimates made using Migromat® alarms during the present project. Thus, the contribution that can be made by a fishery located upstream of a hydropower dam to local knowledge of eel migration peaks was confirmed in the present study. Likewise, scientific analyses of catch and environmental data such as those obtained in long–term eel studies at Killaloe provide much more accurate and potentially useful predictions (Cullen & McCarthy, 2003). As illustrated by results presented in Tables 12–17, Migromat® alarms often failed to predict peak runs (defined by four alternative thresholds). Furthermore, Migromat® alarms were often associated with lunar periodicity (Fig. 8) and rising discharge levels (Fig. 9). These may have stimulated eel activity, by detection of environmental stimuli such as lunar rhythm and hydro-chemical cues. However, direct observations of environmental conditions, including discharge rates and weather, enables researchers and fishing crews to identify nights in which large quantities of eels migrate.

Expected loss of revenue caused by turbine shutdown/spillage of water based on Migromat® alarms is difficult to estimate. The varying commercial potential of stored water reserves over the annual cycle, and the statutory obligations in respect of spillage when flooding of agricultural land and urban settlements are threatened, complicate estimation of a monetary value. It should also be noted that discharge has a significant effect on eel migration, particularly on the lower River Shannon (Cullen & McCarthy, 2003; McCarthy *et al*, 2008). Turbine shutdown, resulting in reduced discharge, may inhibit silver eel migratory tendencies. Therefore, this measure would have to be combined with spillage to simulate migration and provide an alternative, safe route. However, some spillways may not be structurally designed for such prolonged releases of water, and flooding issue may arise in downstream areas not suitable for excessive discharge (*e.g.* 'old' River Shannon channel). Depending on the structure, spillways may not provide injury–free passage for silver eels, but in most cases will have much lower mortality rates than turbine passage (Haro et al., 2003; Watene & Boubee, 2005).

It is not possible, using River Shannon data, to rule out the potential use of Migromat® technology at other sites, such as French river systems lacking silver eel fisheries, in which eel migrations are not currently amenable to prediction. Likewise, perhaps with further research the predictive capacity of the Migromat® system could be improved. However, the present project partners were specifically requested by the developers of the Migromat® system (IfAÖ) not to explore the technical basis of the system and this restriction is respected in this report. However, all involved in the study have developed new ideas and an improved understanding of silver eel behaviour and of eel migratory phenomena in general. This improved knowledge may provide a platform for development of improved biomonitoring or predictive modelling tools that can be used for eel conservation by hydropower operators.

8. Conclusions

The two–year evaluation of the predictive capacity of the Migromat® early warning system was carried out between 2008–2010. The experimental site was located adjacent to Killaloe eel weir, on the lower River Shannon, where daily silver eel catches were monitored. Despite extreme weather conditions during the second year of the experiment which interrupted fishing for a 17–day period, adaptation of the project work programme (using a novel DIDSON count protocol) enabled the evaluation of the Migromat® system to be successfully completed.

Overall, Migromat® appears to be a relatively poor predictor of eel catches at the Killaloe eel weir and would be of very limited value as a biomonitoring tool in respect of a hydropower station located at this site. Using various alert and analytical models, just 14.3–20.8% of the total catch in 2008/2009 and 18.1–29.1% of the total catch in 2009/2010 would have resulted from Migromat® predictions, and this would be unlikely to satisfy the requirements of Ireland's National Eel Management Plan.

The effectiveness of the Migromat® system is likely reduced as alerts were generally received *during* peak migration events, rather than *before*, and hence a significant proportion of silver eels migrated undetected. However, the fact that Migromat® alerts (in 2009/2010) corresponded to just 5.1–7.4% loss of generation is promising. With further development, the predictive capacity of the system may be improved, and it could be an effective silver eel conservation measure on other hydropower–regulated river systems.

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Appendix 1

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Appendix 2

The Killaloe catch in relation to Migromat® alarms/turbine shutdown are illustrated below for each model (instant, 12:00 and 18:00). The 2008/09 graphs refer to the 98–day Migromat® operational fishing period and the 2009/10 graphs refer to the continuous fishing period (02/11/2009 to 17/01/2010).

2008/09

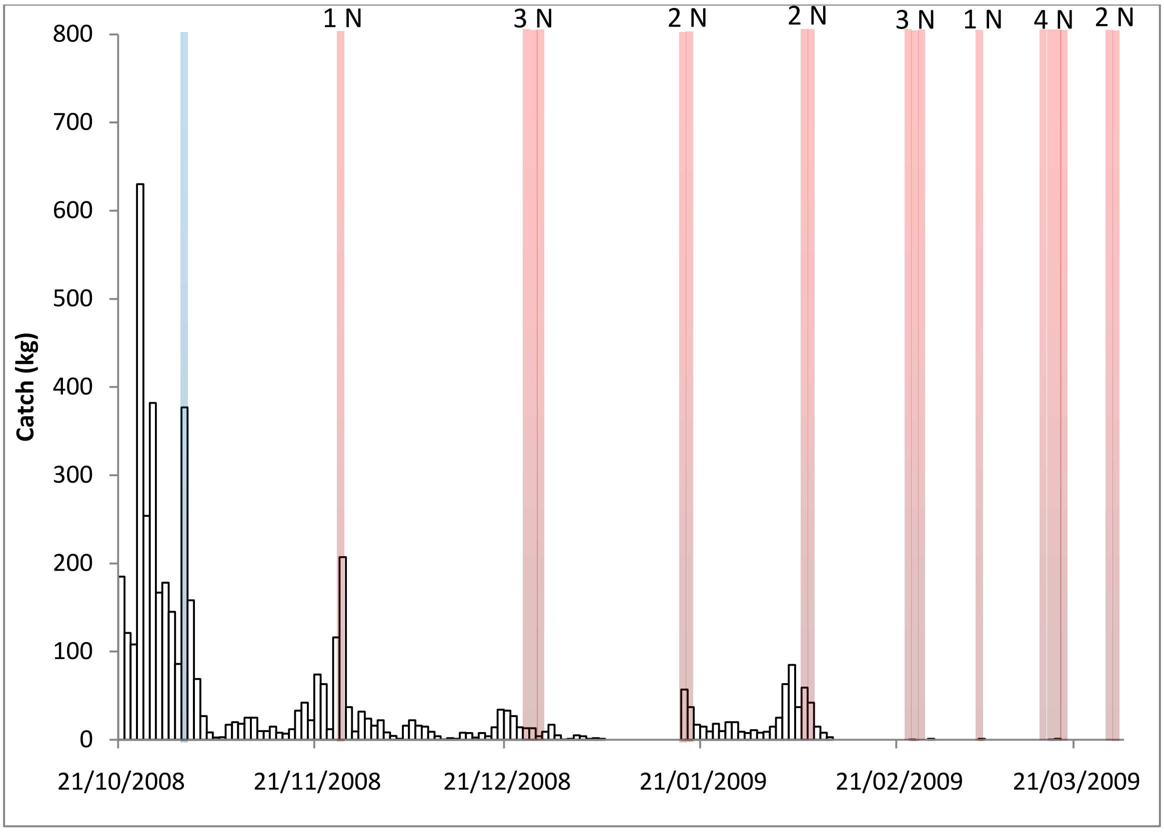

Figure 11. Instant model. Blue indicates the date Migromat® was declared operational, red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.

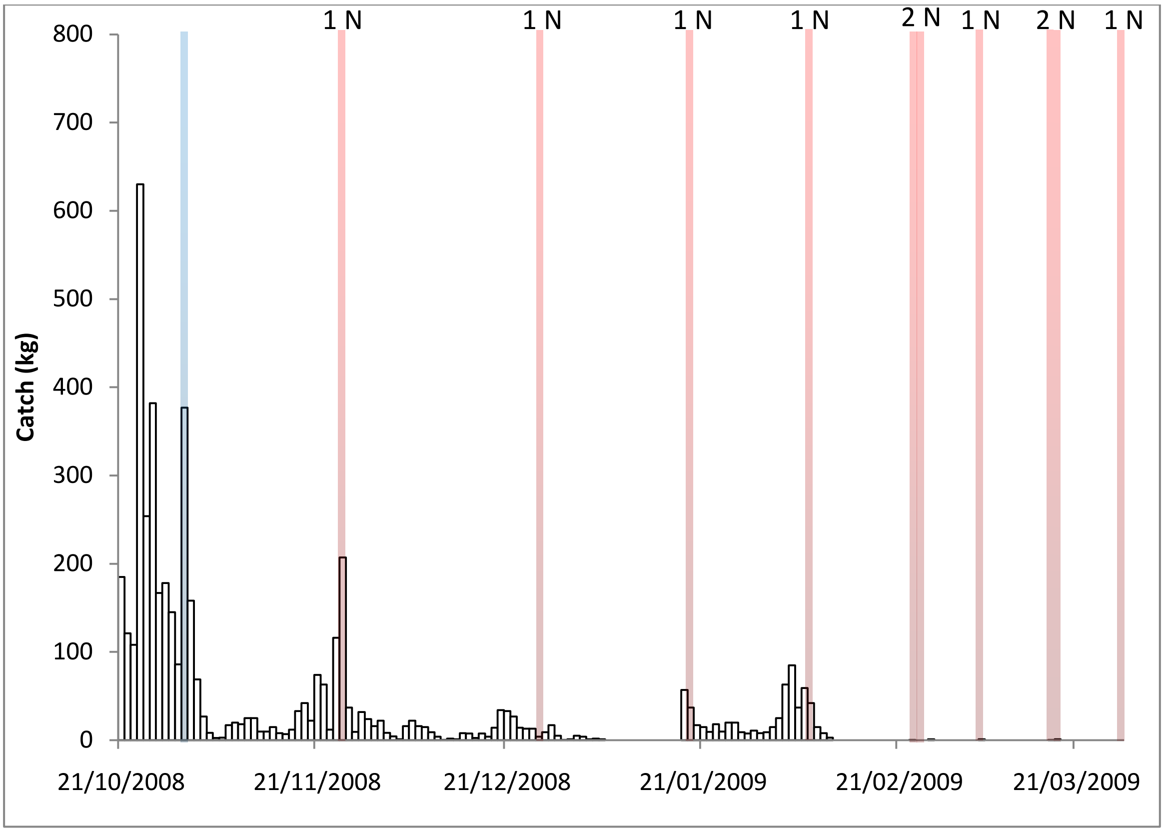

Figure 12. 12:00 model. Blue indicates the date Migromat® was declared operational, red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.

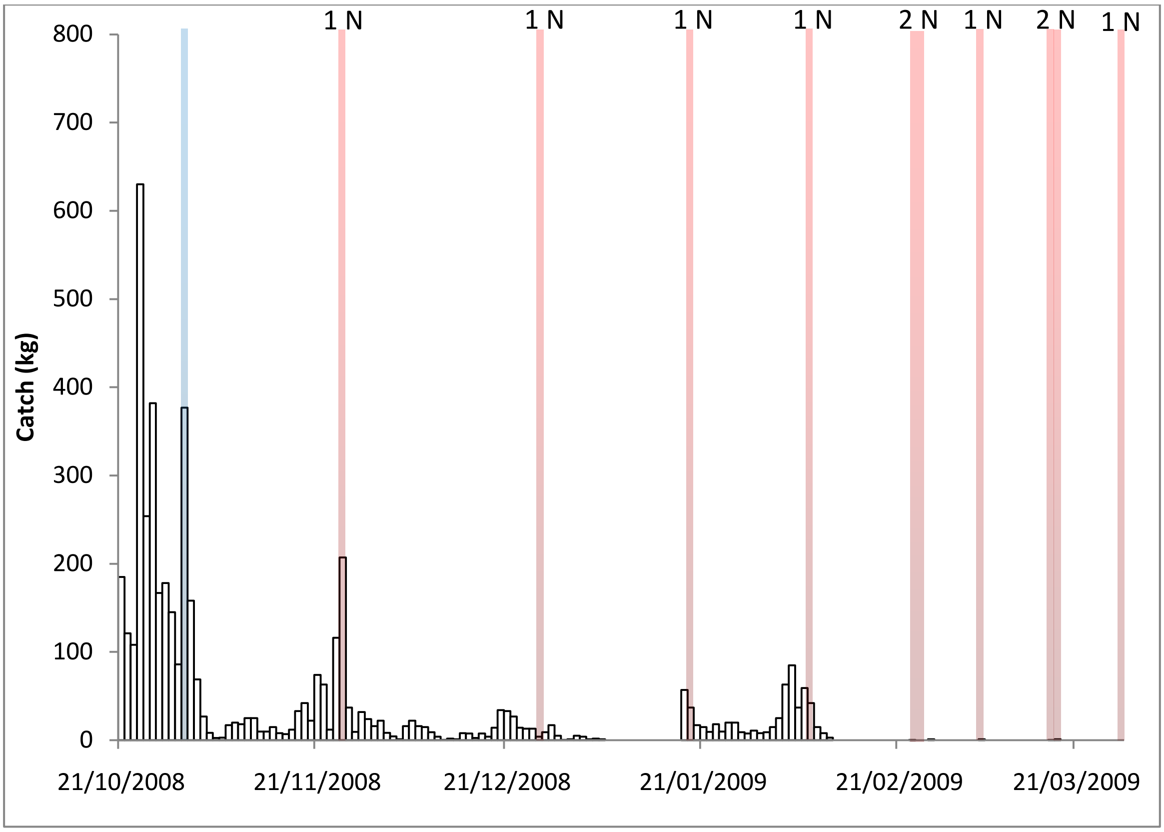

Figure 13. 18:00 model. Blue indicates the date Migromat® was declared operational, red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.

2009/10

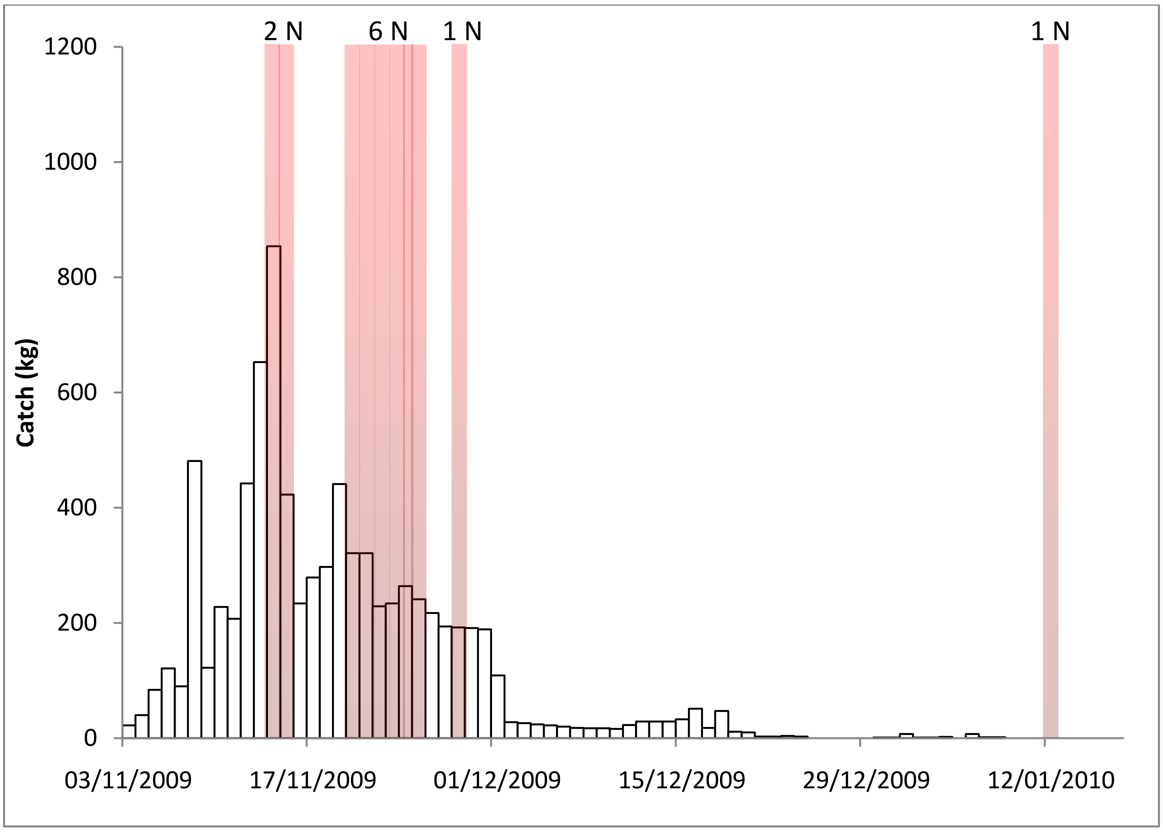

Figure 14. Instant model. Migromat® was declared operational on the 16/08/2009. Red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.

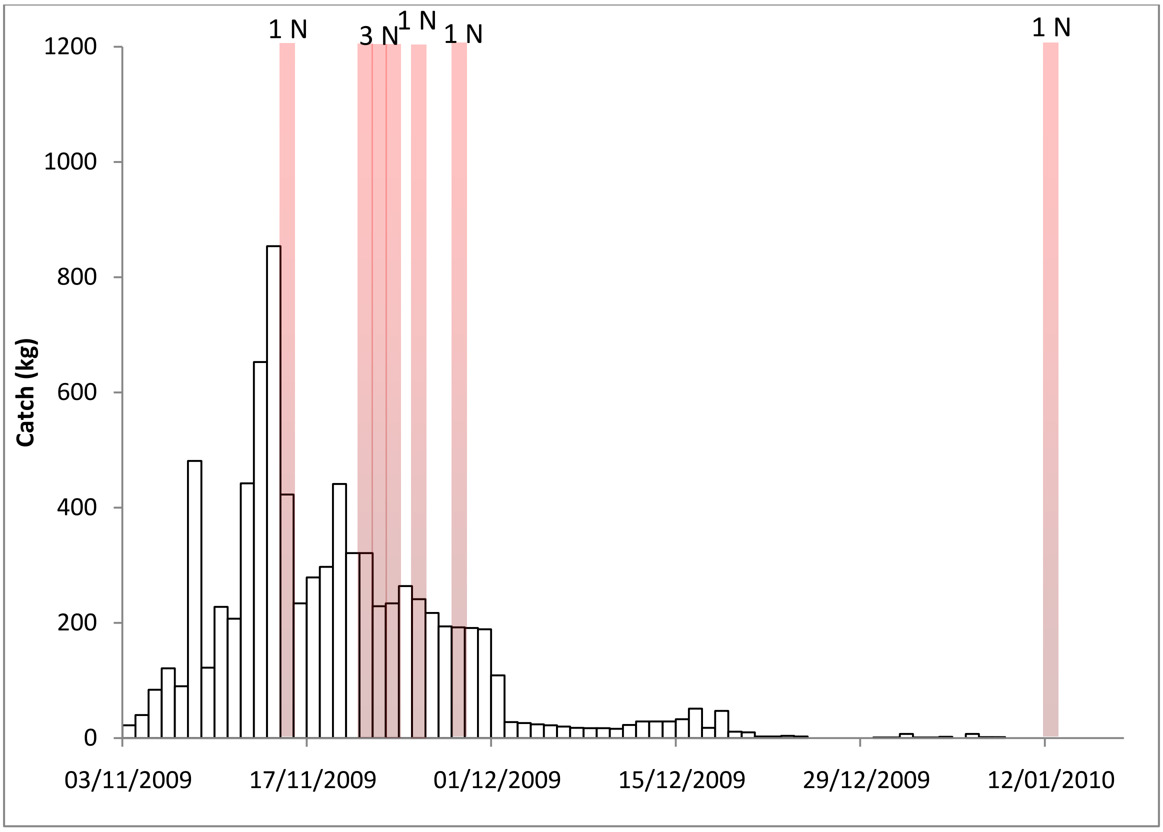

Figure 15. 12:00 model. Migromat® was declared operational on the 16/08/2009. Red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.

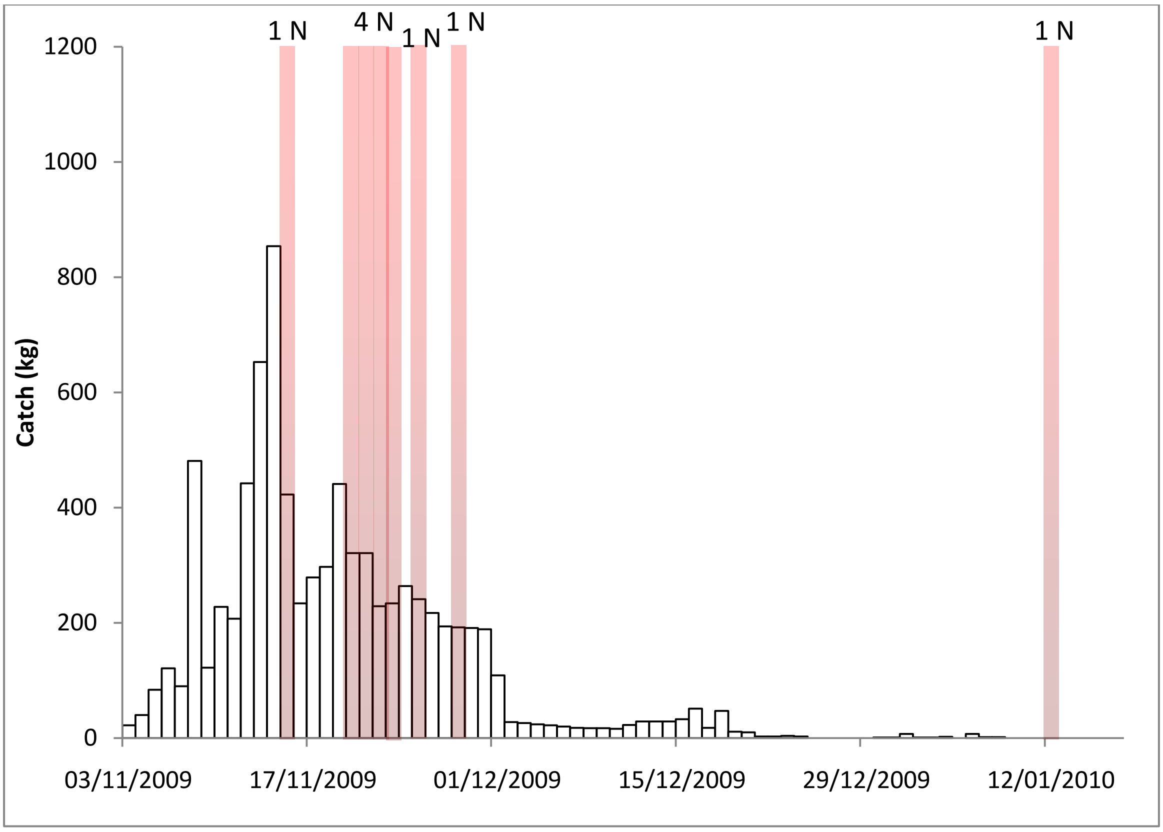

Figure 16. 18:00 model. Migromat® was declared operational on the 16/08/2009. Red represents the duration (*i.e.* number of consecutive nights) of alarm events and turbine shutdown.