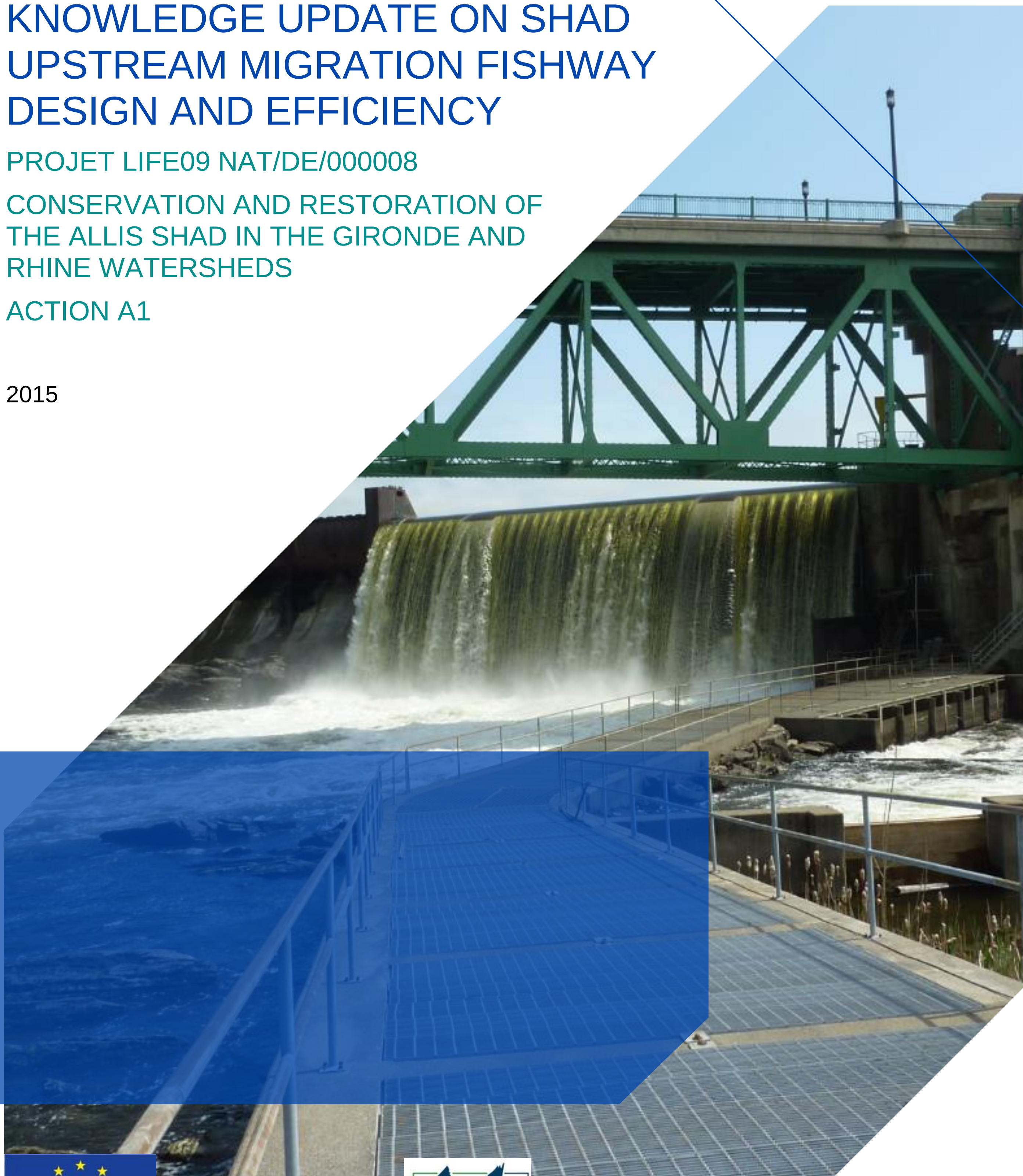
KNOWLEDGE UPDATE ON SHAD UPSTREAM MIGRATION FISHWAY DESIGN AND EFFICIENCY

PROJET LIFE09 NAT/DE/000008

CONSERVATION AND RESTORATION OF THE ALLIS SHAD IN THE GIRONDE AND RHINE WATERSHEDS

ACTION A1

2015



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ACTION A1

Office National de l'Eau et des Milieux Aquatiques

Project WSP #: 141-22223-00
Date: 2015

ONEMA
Office national de l'eau
et des milieux aquatiques

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WSP France S.A.S.
3, rue des Charrons - Espace Hadrien
31700 Blagnac – France

Tél : +33 5 31 22 44 38
www.wspgroup.com

NATURA 2000

SIGNATURES

François Groux, Engineer
WSP

Jean Therrien, Biologist
WSP

Matthieu Chanseau, Doctor of Biology
ONEMA

Dominique Courret, Engineer
Pôle Ecohydraulique ONEMA - IMFT

Stephane Tétard, Engineer - Research Scientist
EDF

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PRODUCTION TEAM

ONEMA

Project Manager	Jean-Michel Cardon
Team Experts	Matthieu Chanseau Dominique Courret, Pôle Ecohydraulique - IMFT

EDF

Team Expert	Stéphane Tétard

WSP

Project Manager	Cécile Llovel
Project Team	François Groux Jean Therrien Claudine Breton
Voluntary Contribution of	Michel Larinier François Travade
Editing	Nancy Paquet
Translation	Joanie Mailloux Johanne Fortier Sara Anne Bilodeau

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1 INTRODUCTION

1.1 STATUS OF THE SHAD (ALOSA ALOSA) IN EUROPE

Allis shad is found on the southern coasts of Europe, south of Iceland and Norway (Maitland & Hatton-Ellis, 2003).

Historically, true Allis shad *Alosa alosa* populated watercourses from Morocco to Germany, and up to the British Isles. However, the species seems to be concentrated nowadays in the central part of its distribution area, between France and Portugal (Maitland & Hatton-Ellis, 2003).

At the end of the 19th century, Allis shad populations started declining in the vast majority of European watercourses, and even completely disappeared in several rivers (Elbe, Rhine, Meuse, Tamise, Seine, Sébou, etc.), due to dam construction, environmental degradation and over-harvesting (Baglinière & Elie, 2000). Global warming could pose an additional threat to the species: decrease of watercourse flows, increases in water temperatures, change in oceanic and estuarine conditions, etc.

France is still home to numerous Allis shad populations spread over the main rivers on the Atlantic seaboard and the North Sea. The population of the Gironde-Garonne-Dordogne catchment, considered for a long time as the biggest shad population in Europe with upstream migration sometimes exceeding 700,000 fish per year (Chanseau & *al*., 2005), has, however, significantly declined since the early 2000s (Rougier & *al.,* 2012*)* and is now severely at risk.

Once abundant in the Rhine catchment, the species has been greatly affected by human activity (major refurbishment of the Tulla dam in the 19th century, construction of hydroelectric dams, environmental conditions). A reintroduction project was initiated in 2007, as part of a Life Programme (Scharbert, 2015). After verifying the presence of favourable fish habitats, the purpose of this program is essentially to replenish the population, to monitor the offspring for a few years and check for natural spawning. The first results are encouraging.

In Great Britain and Ireland, the species is found in coastal waters but there are very few watercourses where spawning occurs (Aprahamian & *al*., 1998; Henderson, 2003; Doherty & *al*., 2004). Presently, the Tamar appears to be the only river with an Allis shad population (Gratton & Kibel, 2015).

Historically, all main watercourses of the Iberian Peninsula (Portugal and Spain) were colonised by the species. Construction of dams highly impacted the populations (Costa & *al*., 2001), and today only a few rivers are still colonised, such as the Minho and Mondego (Mota, 2014).

In conclusion, the European shad (*Alosa alosa)* is in a vulnerable position throughout its distribution area. It is included in the Red List Threatened Species of the International Union for Conservation of Nature (IUCN), and it also listed in Appendix III of the Bern Convention and in the Habitats Directive. This may be explained in part by the presence of dams on the watercourses, which prevent all, or part of the population from reaching habitats more suitable for the reproduction of adults and growth of juveniles, as well as the degradation of the environment and overfishing.

1.2 THE AMERICAN SHAD (*ALOSA SAPIDISSIMA*): CLOSE RELATIVE OF THE EUROPEAN SHAD

It is generally accepted that the American shad *Alosa sapidissima* is a close relative of the European shad. Their behaviour and biological characteristics are similar (Table 1-1). The major difference is the iteroparity: the proportion of American shad that survive reproduction and spawn several times can be high, depending on the watercourses, while the vast majority of European shad spawners die after reproduction.

The American shad is an anadromous species whose distribution area extends from Eastern Canada and New England down to Florida (United States). The largest populations along the US coast are located from Chesapeake Bay (Virginia and Maryland) up to Massachusetts (ASMFC, 2007).

Globally, shad populations are declining due to dam construction, the degradation of their habitats and over-harvesting (Limburg & Waldman, 2009). While originally more than 130 watercourses were colonised by the species on the Atlantic coast, less than 70 still have populations today (Limburg & *al*., 2003).

Major efforts have been put forth to restore the populations: reduction of fishing, construction of fishways, restocking, etc. Stocks remain nonetheless low in numerous rivers such as the Susquehanna. Good levels are maintained in some rivers (Connecticut), and even appear to be increasing in others, such as the Potomac and Rappahannock (Latour & *al.*, 2012) (http://www.chesapeakebay.net).

The species was first introduced on the U.S. West Coast in 1871, in the Sacramento and Columbia rivers. Numbers have considerably increased starting in the 60s, even raising concerns regarding the impact on other fish species, such as the salmonidae (Hasselman & *al*., 2012; Hinrichsen & *al*., 2013).

Table 1-1 Main Biological Characteristics of the European (*Alosa alosa*) and the American Shad (*Alosa sapidissima*), according to Baglinière & Elie (2000); MacKenzie & *al.* (1985), Limburg & *al*. (2003), and Greene K.E. (2009),

PARAMETER	EUROPEAN SHAD (*ALOSA ALOSA*)	AMERICAN SHAD (*ALOSA SAPIDISSIMA*)
Average Length (cm)	45 - 70 (Baudoin, & *al.*, 2014)	35 - 55
Average Weight (kg)	1.5 - 3.5	1-3
Migration: Water Temperature (°C)	10 - 15	13-20
Migration Period	February - June	Period varies depending on temperature. Extends from November in Florida to June in Quebec
Spawning: Period	May - August	Period varies depending on temperature. Extends from January in Florida to July in Quebec
Multiple Spawners	Low (<2%)	Low in the South (0% in Florida) and increases towards the North (70% in New Brunswick, Canada) Can spawn up to 6 times during its lifetime

1.3 FRAMEWORK AND OBJECTIVES

In France and Europe, the majority of watercourses colonised by the European shad (Alosa alosa) are separated by various obstacles (hydroelectric power dams, navigation, mills, stability threshold, etc.) which often have a significant impact on the populations; preventing fish from reaching the most suitable habitats for reproduction and growth of juveniles.

Overcoming obstacles is a very important issue for the management and restoration of the European shad populations. The present work does not address downstream migration. Indeed, nearly all mature Allis shad die after reproduction, and the impact on shad juveniles following their passage through turbines is a priori limited, thanks to their small size and to the characteristics of the hydroelectric developments. Moreover, there are fewer hydroelectric generating stations on the migration path of the shad than for other fish species who migrate further upstream (most notably salmonids).

The information regarding the impact of these structures on European shad, its behaviour at the obstacles and in fishways is fragmented. There is more significant information on the American shad, especially for the U.S. East Coast. It thus seemed important to summarise the experience gained in France, Europe and the U.S. so as to update the design criteria currently used for the sizing of European shad fishways.

To this end, and as part of the LIFE09 NAT/DE/000008 program, the *Office National de l'Eau et des Milieux Aquatiques* (ONEMA) mandated WSP to produce the following:

→ Knowledge synthesis on the efficiency of the various fishways used in France and Europe for the Allis shad;

→ Assessment of knowledge and experience on the efficiency of fishways for the American shad (Study trip to the U.S. East Coast, May 18-29, 2015);

→ Synthesis report on the current knowledge and main recommendations to be considered in order to minimise the impact of obstacles and maximise the efficiency of fishways for the upstream migration.

The present document is the synthesis report.

2 BIOLOGICAL FACTORS AND MIGRATION PATTERN OF THE SHAD

2.1 SWIMMING ABILITY

Shad cannot jump and thus have to swim to overcome obstacles.

They are considered to be good swimmers, even if they have nowhere near the swimming ability of large migratory salmonid fish, both in terms of velocity and stamina.

It seems that the European shad (*Alosa alosa*) can withstand velocities ranging from 3.1 to 4.7 m/s for a duration of about 6-7 seconds, and at a temperature of 16-17 °C (Litaudon, 1985). Maximum velocities range from 4.1 to 6.1 m/s. Thus, flows of 2 m/s on a few dozen metres represent a major problem for the species (C.T.G.R.E.F., 1981). In France, as part of the dam passability expertise, maximum velocities ranging from 3.5 to 5 m/s were chosen, which take into account the variation in the size and physiological state of fish, or in the water temperature (Baudouin & *al*., 2014).

Observations made by Weaver (1965) and Haro & *al*. (2004) revealed that the American shad (*Alosa sapidissima*) can cross more than 6 m in flow velocities of 4.15 m/s, and an average of 5 m in flows of 4.5 m/s. According to Castro-Santos (2005), their maximum swimming velocity can reach 5 to 10 times their body length per second, for respective durations of 5 seconds and 2-3 seconds.

2.2 MIGRATION PATTERN

Only information with a more or less direct link to the overcoming of obstacles are presented hereinafter. It was in part taken from the Larinier & Travade (2002) and Haro & Castro Santos (2012) publications.

Shad travel in schools. Splitting of these schools could be problematic for the migration, specifically in fishways with smaller open dimensions or if the flows are ill-suited (recirculation regions, corners, etc.) (Haro & *al.*, 2001). This could explain the shad’s behaviour in fishways often characterised by frequent fall-back activity which could result in the entire school of fish moving downstream.

Migration in rivers and streams, and at the foot of obstacles, occurs more often during the day (Baglinière & Elie, 2000). Shad leave after sunrise and return to a downstream pool at sundown (Barry, 1982; Steinbach & *al*., 1986; Moser & *a*l., 2000; Grote & *al*., 2014). As such, most of the fish that enter and pass through the fishways are observed during the day, for both the European and the American shad (Chanseau & *al*., 2000; Haro & Kynard, 1997; Sullivan & *al*., 2004). If the shad is still in a fishway at the end of the day, it is likely to fall back and exit (Haro & Kynard, 1997; Sullivan & *al.*, 2002).

Similarly, the fish seem to be highly sensitive to brightness variations in fishways, which could prevent their upstream migration.

They swim in the water column, but not directly under the surface. At the Lowell tailrace, on the Merrimack River (U.S. East Coast) (ALDEN, 2011), it was observed that the vast majority of fish move at depths ranging from 1.5 to 4.5 m.

Fish seem to seek out regular flow of water seams with parallel lines and avoid heavy turbulence vortex areas and white waters (eddies downstream from a fall, jump, downstream from turbines) which is difficult for them to deal with. Barry & *al.* (1986) indicate that the presence of highly aerated water likely represents a barrier for the shad. Normandeau and Gomez and Sullivan (2011), regarding the Conowingo dam site on the Susquehanna River (U.S. East Coast), noticed that fish avoid the area located directly downstream of the Kaplan, which is subjected to severe turbulence. Castro Santos & *al.* (2014) also highlights that fish rarely stay at the foot of the Gate House (Turners Falls – Connecticut River, U.S. East Coast) due to unfavourable hydrodynamic conditions. At the Lowell site on the Merrimack River, ALDEN (2011) also shows that the shad prefer to stay in areas located near riverbanks in the tailrace, especially as turbinated flows are significant (Figure 2-1). They pass through areas of heavy turbulence when exiting the turbines, but barely remain there.

Observations show that shad get easily stuck in corners and recirculation areas. These observations were made for both the American shad in the U.S., at the Holtwood site, especially on the Susquehanna River (see Section 4.4), and the European shad in France (C.T.G.R.E.F., 1981).

Visual observations made at several sites, as well as the various telemetric surveys, highlighted that the exploratory behaviour of the shad downstream of the obstacles and their efforts to move beyond these structures are less than those of other species such as the salmon. Thus, for example, the presence frequency of the American shad downstream of the structures appears to be rather low: only a few times during the migration period (Barry & *al.*, 1982; Barry & *al.*, 1986; ALDEN, 2011; Normandeau and Gomez and Sullivan, 2011; Normandeau and Gomez and Sullivan, 2012). Furthermore, their stationary and exploratory times are limited and vary from a few hours to a few days at the most (Sprankle, 2005; ALDEN, 2011). For the Conowingo dam on the Susquehanna River, Normandeau and Gomez and Sullivan (2011; 2012) points out that the median presence time is very short, ranging from 12 to 36 minutes, depending on the fate of the shad (whether or not there is upstream passage).

For the European shad, there are only partial data and only involve a few individuals. Steinbach & *al.* (1986) stated that on average, fish were present in front of the Saint-Laurent-des-Eaux obstacle on the Loire twice and then remained an average of 22 consecutive hours immediately downstream (up to 500 m downstream from the obstacle). On the Dordogne and the Garonne rivers, near the Golfech, Bergerac and Tuilières dams, Verdeyroux & *al.* (2015) showed that fish came only a few times at the foot of the structures (average of 2.1 times) and only stayed there for a limited time (15.3 hours on average).

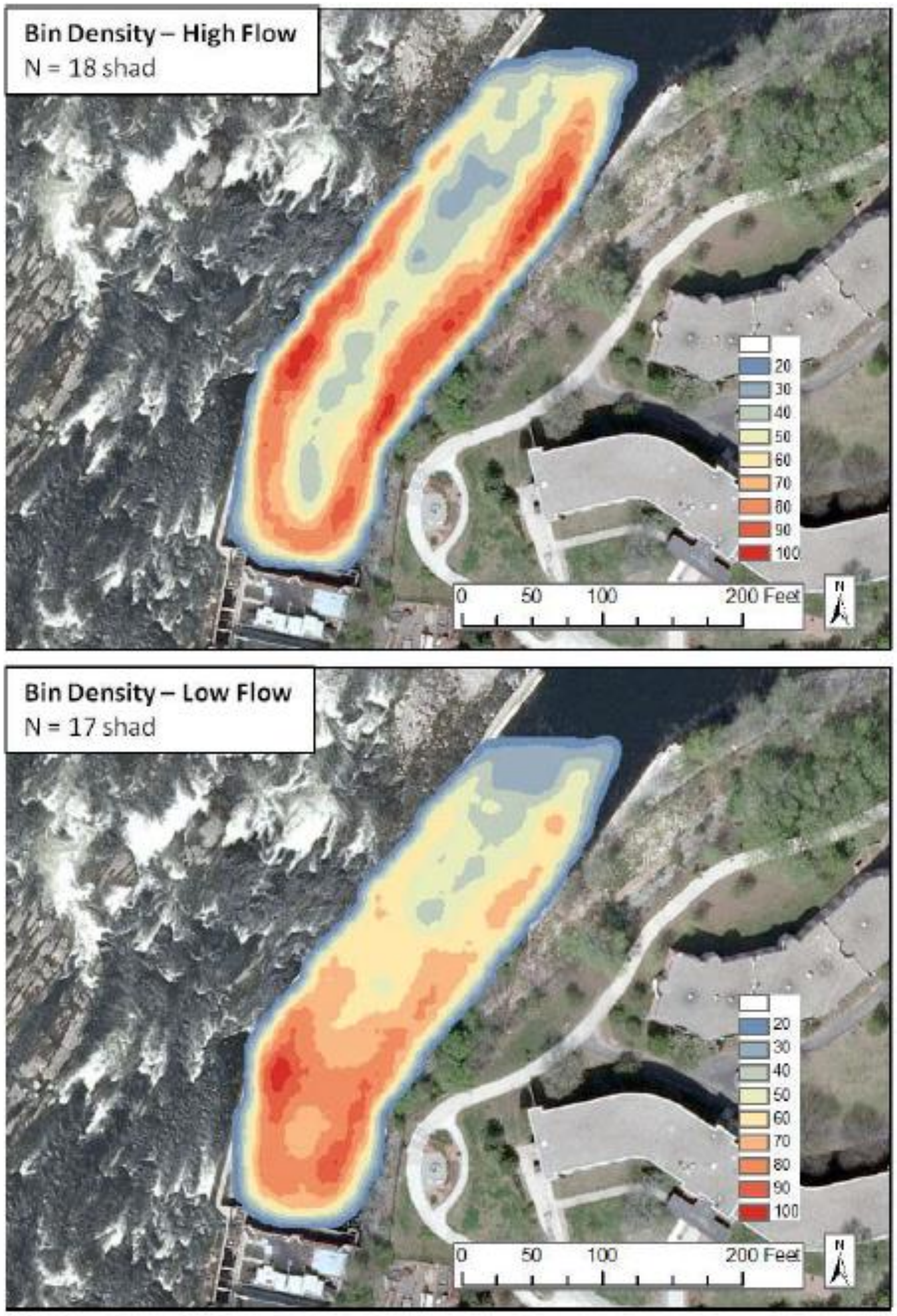

Figure 19. Bin density of 3D positions (distribution) of shad in the Lowell tailrace during periods when tailrace flow was above (top image) and below (bottom image) the mean (4493 cfs) for the study period. Distribution is calculated as a percent of individuals occupying a bin. Bins are delineated in a 10 ft x 10 ft grid throughout the tailrace. Data in inset boxes are means.

Figure 2-1 Example of Preferential Shad Distribution along the Banks of the Lowell Tailrace and Impact of Hydrodynamic Conditions in the Tailrace, Lowell hydroelectric plant, Merrimack River, USA. (ALDEN, 2011).

3 SYNTHESIS OF KNOWLEDGE ON SHAD PASSAGES IN FISHWAYS

A synthesis of available knowledge on shad passages in fishways, both in the United States (Connecticut, Merrimack and Susquehanna rivers on the East Coast, and Columbia River on the West Coast) and in Europe (primarily in France) is presented. This allow for the introduction of elements regarding the migration rate of the shad and the environmental parameters (flow and temperature) during migration. However, it is important to note that these rates are more or less influenced by the efficiency of the fishways, the configuration of the hydroelectric development, the hydrology, etc.

The main features of the obstacles, fishways, and shad passages are presented in a series of photographs, as well as in Table 3-1 and Table 3-2.

On the U.S. East Coast (Merrimack and Susquehanna rivers, Holyoke dam on the Connecticut River), the fishways are operational only during the day, normally from 8 AM to about 8 PM due to the diurnal migration of the American shad but also to limit the loss of non-turbine flow and allow the fish to be counted. Indeed, on the majority of the sites, fish are counted manually and directly on site by counters posted behind a viewing window. To this day, video has only been used at Turner Falls, Vernon (Connecticut River) and at York Haven (Susquehanna River).

In Europe, data have been recorded at 29 control stations from where shad passages are observed. These stations include 28 located in France and one in Portugal on the Minho River (Almeida, pers. com. 2015). Only dams where there is significant migration are presented. Gratton & *al.* (2015) states that each year, only a few dozen individual fish passed through the fishway at Gunnislake Weir, which is located on the Tamar River in Great Britain.

Table 3-1 Main Features of the Obstacles and Fishways where Shad Passages are Counted on the U.S. East Coast.

River	Site	Distance from Ocean (km)	Mean Annual Discharge (m^3/s)	Average May Flow (m^3/s)	Max Diverted Flow(m^3/s)	Type of Fish Ladder	Number of Operational Entrances in 2015	Total Flow in Fish Ladder (m^3/s)	Year of Monitoring	Passage Counts Min.	Passage Counts Moy.	Passage Counts Max.
Susquehanna	Conowingo	16	1165	1365	2400	Lift	2[1]	8.5	1997 - 2015	83,41	58,113	193,574
	Holtwood Plant	39	1090	1280	1700	Lift	2	17	1997 - 2015	21	20,099	109,976
	Holtwood Spillway					Lift	1	5.7				
	Safe Harbor	50	1060	1245	3200	Lift	2	17	1997 - 2015	8	15,324	89,816
	York Haven	88	980	1150	480 [2]	Pool and weir (serpentine)	1	7.5	2000 - 2015	0	1,929	16,200
Merrimack	Lawrence	48	245	355	210	Lift	1	3.5	1983 - 2015	1,205	25,550	86,857
	Lowell Plant	70	225	330	215	Lift	1	3.5	1989 - 2015	383	4,647	17,310
Connecticut	Holyoke Plant	139	505	680 [3]	235	Lift	2	6.8	1967 - 2015	19,000	259,901	720,000
	Holyoke Spillway					Lift	1	5.7				
	Turners Falls Cabot Station	198	395	540	390	Pool and weir (Ice Harbor)	1	10.5	1980 - 2015	11	14,773	60,089
	Turners Falls Gate House				500	Pool and weir (2 slots)	2	14.3				
	Turners Falls Spillway				Spillway	Pool and weir (Ice Harbor)	1	9				
	Vernon	228	365	500	485	Pool and weir (Ice Harbor + serpentine)	1	7.3	1981 - 2015	9	7,265	39,791
	Bellow Falls		295	465	410	Pool and weir (1 slot)	1	2.3	44 shads in 2015			

1 Only one in operation according to the turbine management plan.
2 The fish ladder is located in the Susquehanna inlet fed by an average flow of 57 m^3/s.
3 A flow up to 190 m^3/s is diverted into a channel located directly upstream of the plant.

Table 3-2 Main Features of the Obstacles and Fishways where Shad Passages are Counted in Europe.

Country	Watercourse	Obstacle	Distance from the Sea (km)	Mean Annual Discharge of Watercourse (m^3/s)	Average Flow in May (m^3/s)	Max Diverted Flow (m^3/s)	Type of Fishway	Flow in Fishway (m^3/s)	Max. Internal Fall (m)	Year of Monitoring	Passage Counts		
											Min	Moy	Max
France	Claies de Vire	Vire	28.4	13	7,5	--	Pool and weir (slots)			2002 - 2015	1,728	4,154	8,895
France	Orne	Feuguerolles - Bully	33	23	16	--	Baffle fishway (overactive) until 2010 then Pool and weir (slot)			1994 - 2015	5	121	499
France	Seine	Poses	156.5	479	522	150	Pool and weir (slots)	4 - 6.5	0.25	2008 - 2012	950	2,112	3,870
France	Vilaine	Arzal	8	75	50	--	Pool and weir	2	0.3	1996 - 2015	38	1,135	4,242
France	Aulne	Chateaulin	35	25	16	--	Pool and weir (slot)			2009 - 2015	179	1,318	2,891
France	Vienne	Chatellerault	270	110	115	100	Pool and weir (slots)	1.5	0.3	2004 - 2015	135	2,427	9,538
France	Creuse	Descartes	260	75	87	80	Pool and weir (slots)	2	0.3	2007 - 2015	3	1,671	9,050
France	Loire	Decize	576	135	155	160	Pool and weir (slots)	2	0.3	1998 - 2015	6	3,859	15,273
France	Allier	Vichy	674	96	133	--	Pool and weir (slot)	3	0.25	1998 - 2015	3	567	3,067
France	Charente	Crouin[1]	100	46	46	--	Pool and weir (slot)	2	0.25	2010 - 2015	1476	3,916	6,038
France	Garonne	Golfech	270	395	590	540	Lift	5	--	1987 - 2015	429	29,439	106,706
France	Garonne	Bazacle	370	190	346	80	Pool and weir (slot)	3	0.3	1993 - 2015	0	3,411	20,546
France	Dordogne	Tuilières	200	270	284	320	Lift (+Pool and weir - slot)	2.5 - 4.5	0.3	1989 - 2015	21	26,536	87,254
France	Dordogne	Mauzac	215	260	272	280	Pool and weir (slot)	3 - 4	0.3	1992 - 2015	0	6,572	50,000
France	Pau	Puyoo	60	81	121	29	Pool and weir (slot)	2	0.3	1996 - 2002	45	419	1,050
Portugal	Mondego	Açude Ponte	30	98	39	--	Pool and weir (slots)	2 - 2.5	0.25	2013 - 2015	966	4,277	7,503

3.1 FISH COUNTS AND TRENDS

On the Connecticut River (see Figure 3-1), migrations have been monitored at the first Holyoke dam since 1967. After a progressive increase in the population up to the beginning of the 1990s to reach a maximum of 720,000 individuals in 1992, passages then dropped sharply. They varied up to the beginning of the 2010s, between 116,000 and 370,000 fish. Recent years have seen a slight increase. Further upstream, the controls started at the beginning of the 1980s. They seem very variable and without any direct link with the number of individuals counted at Holyoke. At Turners Falls and Vernon, on average per year, the counted populations are respectively between 1,500 and 50,000 and between 100 and 30,000 individuals. (http://www.fws.gov/r5crc/pdf/Select_Fish_Passage_Summary_Count_Data.pdf)

On the Merrimack River (see Figure 3-2), fish have been counted since 1983 at the Lawrence dam, the first obstacle encountered by the fish. After an increase in the number of upstream migrations at the end of the 1990s to reach 80,000 individuals in 2001, the numbers then progressively declined and levelled off between 10,000 and 35,000 individuals, without any specific upward or downward trend. At Lowell, further upstream, monitoring started in 1989. The individuals are clearly below those observed in Lawrence even if the evolution of passages is comparable. The passages observed in 2015 at both sites (Lawrence and Lowell) are the most significant since the start of monitoring with respectively 86,857 and 17,310 fish as of July 2nd, 2015. (http://www.fws.gov/northeast/cnefro/returns.html)

On the Susquehanna River (see Figure 3-4), migration monitoring at the first Conowingo obstacle started in 1991. After a significant increase of the populations at the Conowingo Dam until the early 2000s (around 200,000 fish in 2001), upstream migrations have since sharply decreased. The numbers went down to around ten thousand fish in recent years. Further upstream, counting has taken place at Holtwood and Safe Harbor since 1997. An evolution comparable to that of Conowingo can be observed. Only a few thousand fish have passed through the structures in recent years. Like what has been observed further downstream, numbers at York Haven have been declining since the beginning of monitoring in 2000, and only correspond to a few hundred fish in recent years. (http://fishandboat.com/shad_susq.htm)

On the Columbia River (see Figure 3-4), passages recorded at the first obstacle encountered by fish on the Columbia River, the Bonneville dam, which is located about 235 km from the ocean, are high and the monitoring timeframe particularly long. Counting, which started in 1938, shows a progressive and constant increase in the shad population from the beginning of the 1960s up to the 2000s, with a peak of more than 5 million shad in 2004, with the subsequent stabilisation of the numbers (between 1 and 4 million depending on the year). (http://www.nwp.usace.army.mil/Missions/Environment/Fish/Counts.aspx)

In France, the available information is quite heterogeneous depending on the catchment.

Regarding the 4 main catchments colonised by shad:

- in the Adour catchment, the shad population is not well known because there is no control station located far enough downstream on the Adour. However, the condition of the shad has been of concern for more than a decade now (COGEPOMI, 2015);
- in the Garonne – Dordogne catchment, the monitoring carried out for more than 25 years now at the fishways built on both the Tuilières dam, on the Dordogne, and the Golfech dam, on the Garonne, reveal that after a sharp increase in the shad population until the end of the 1990s (up to 193,000 shad in 1996 at the two stations), a steep decline occurred, bringing the number of individuals to only a few hundred by the end of the 2000s. The shad population, once considered the largest population in Europe, is now at risk;

- → in the Loire catchment (see Figure 3-6), the evolution of the population is monitored thanks to 4 stations (Descartes in La Creuse, Châtellerault in La Vienne, Vichy in L'Allier, and Decize in La Loire) located at variable distances from the ocean and on different watercourses. Yearly control of populations varies and ranges from a few individuals to approximately 15,000 shad. In general, the number of passages increased in the mid-2000s followed by a sharp decline. Since the early 2010s, passages have remained low and stable;
- → on the Rhine River, the population, which had almost completely disappeared, seems to have increased in recent years. Monitored populations at Iffezheim and Gambsheim, located more than 600 km from the ocean, went from only a couple of shad per year to more than 150 in 2014. Fish were also observed on tributaries such as the Moselle and Neckar. These results are most likely connected to the Species Restoration Plan (and the associated restockings) implemented as part of the Life Programme (Scharbert & *al*., 2011).

Regarding migratory routes of smaller fish:

- → in the Charente catchment, the monitored populations at the Crouin video station, located at about 100 km from the ocean, which include both the Allis shad (*Alosa alosa*) and the Twait shad (*Alosa fallax*), vary from 1,500 to 6,000 fish per year. For the time being, it is impossible to really detect a trend given the difficulty in differentiating the two species and the small number of monitoring years (started in 2010); (http://www.migrateurs-charenteseudre.fr)
- → four watercourses in Britanny and Normandy (see Figure 3-7) host significant populations and have consistent fish monitoring timeframes. On the Vilaine, in Arzal, the populations, which vary from a few dozen to a little over 4,000 fish every year, have substantially increased in the 2000s. For a decade, the populations remained stable, with a sharp decline in the upstream migration being observed in recent years. Since then, the populations appear to have stabilised to a few hundred fish. On the Vire River, there is a clear trend towards an increase in the population growth: from less than 2,000 shad in the early 2000s, they are now almost 9,000 in 2015. This is the only watercourse in France where monitored populations have increased in recent years. (http://www.peche-manche.com) (http://www.federationpeche.fr/14) (http://www.eptb-vilaine.fr) (http://www.observatoire-poissons-migrateurs-bretagne.fr)

Outside of France, the only place where, to our knowledge, counting is performed is on the Mondego River, in Portugal, at the Açude-Ponte dam at Coimbra. The timeframe is small and cannot be used to determine a trend. The recorded numbers were 7,503; 4,364; and 966 in 2013, 2014 and 2015, respectively (Almeida, com. pers. 2015).

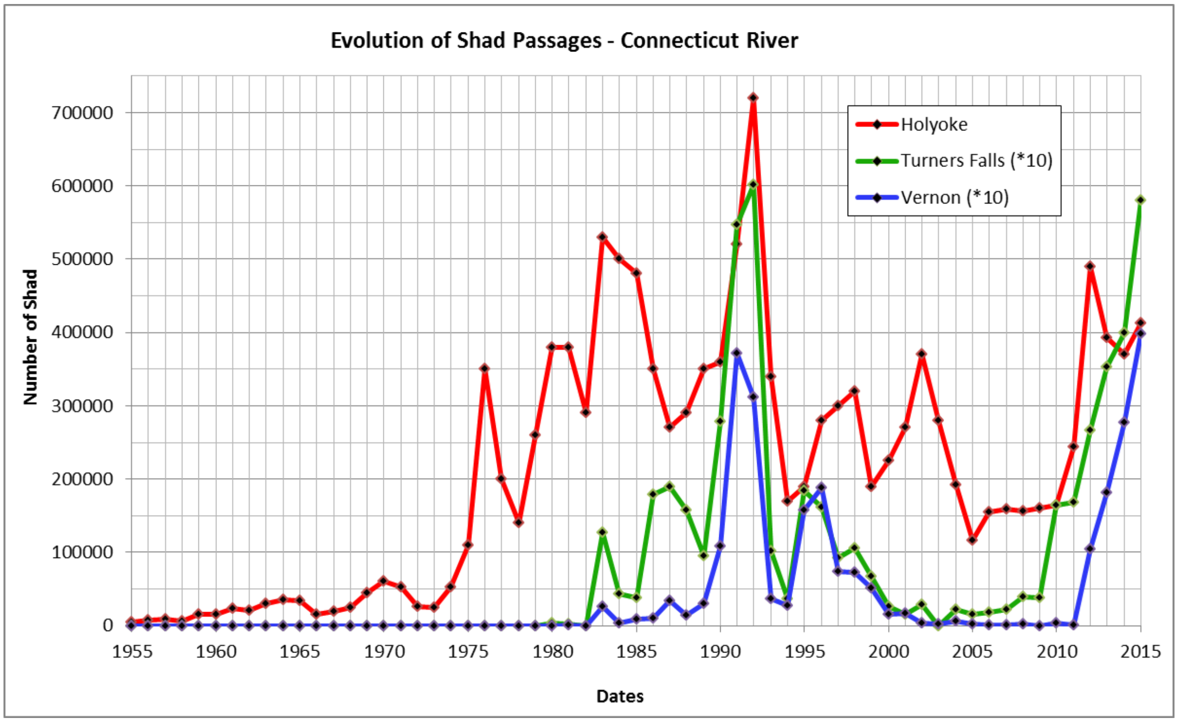

Figure 3-1 Evolution of Shad Passages at the Holyoke, Turners Falls (Gate House) and Vernon Dams on the Connecticut River (1955 to 2015).

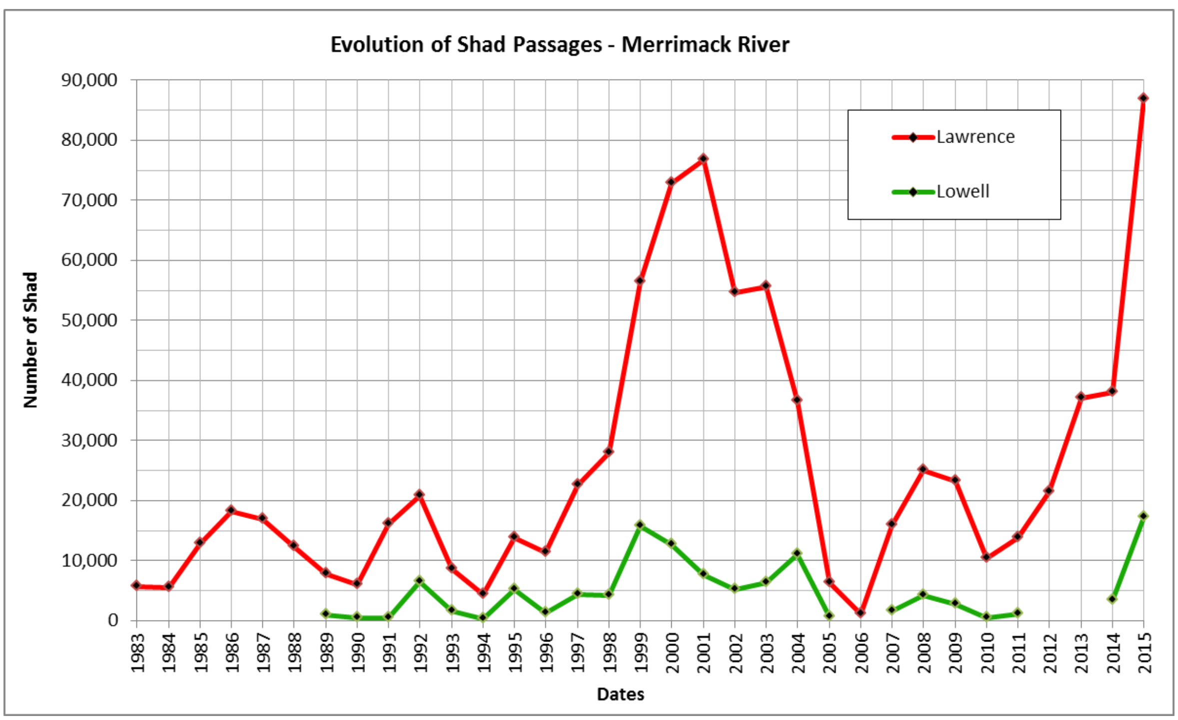

Figure 3-2 Evolution of Shad Passages at the Lawrence and Lowell Dams on the Merrimack River (1983 to 2015).

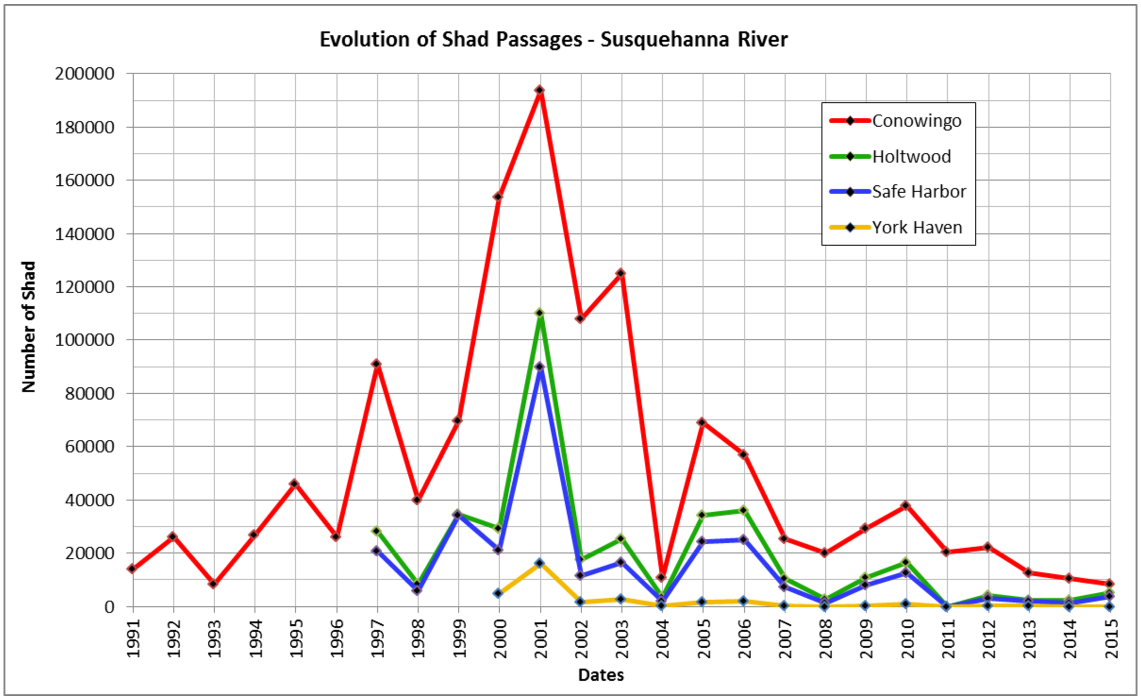

Figure 3-3 **Evolution of Shad Passages at the Conowingo, Holtwood, and Safe Harbor Dams on the Susquehanna River (1991 to 2015).**

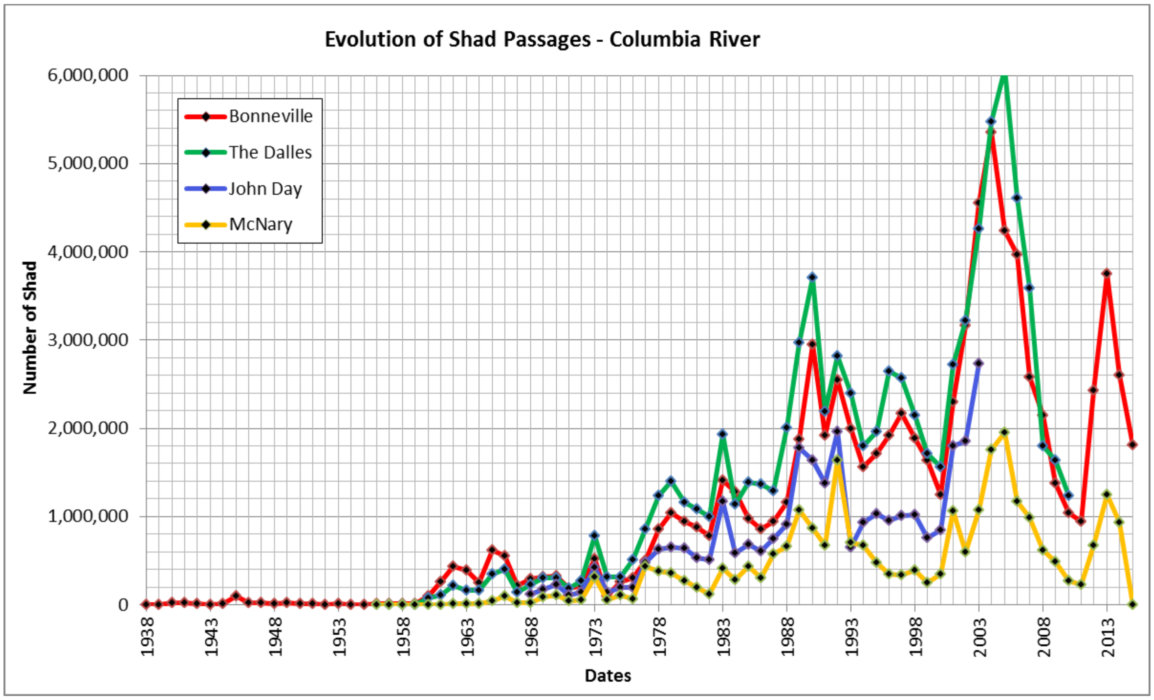

Figure 3-4 **Evolution of Shad Passages at the Bonneville (km 235), The Dalles (km 308), John Day (km 347) and McNary (km 470) Dams on the Columbia River (1938 to 2015) (NB: Unknown consistent passages occur at the Bonneville Lock).**

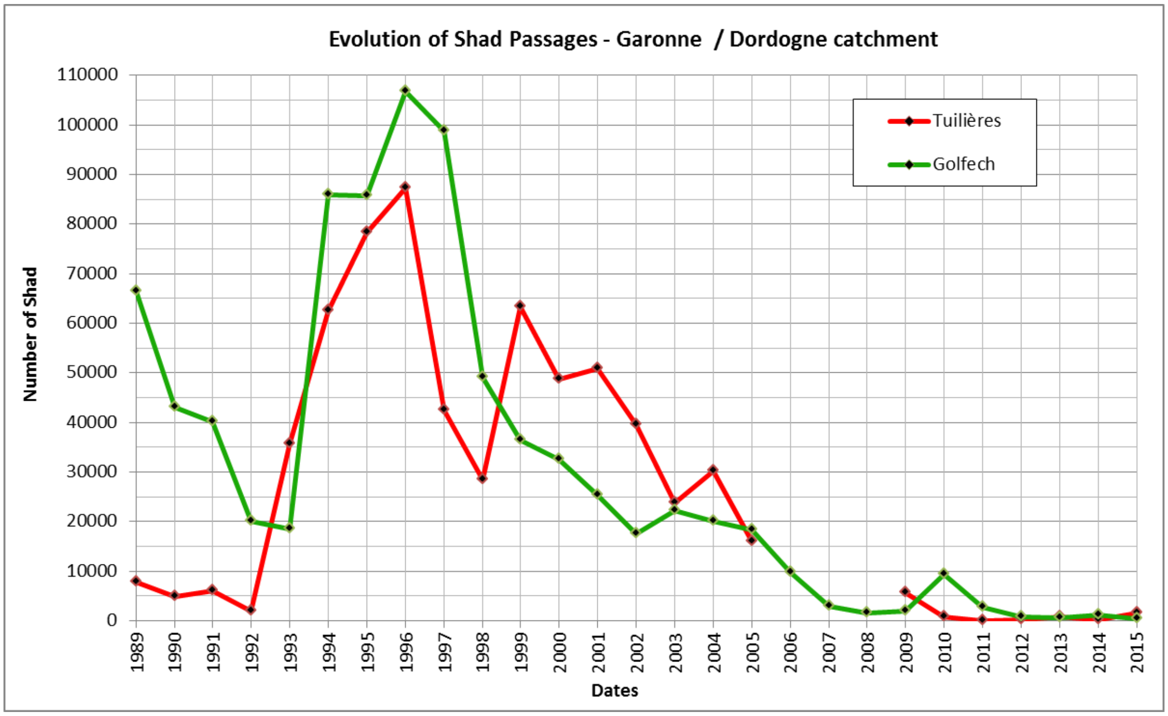

Figure 3-5 Evolution of Shad Passages in the Garonne-Dordogne catchment (1989 to 2015).

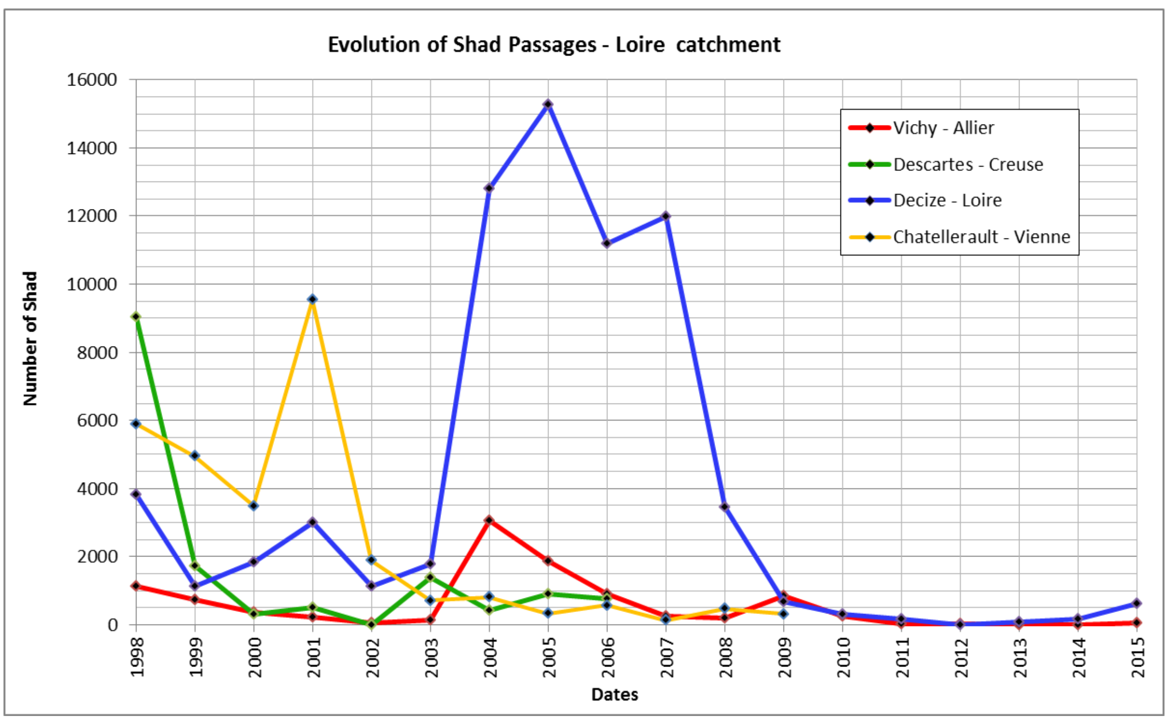

Figure 3-6 Evolution of Shad Passages in the Loire catchment (1998 to 2015).

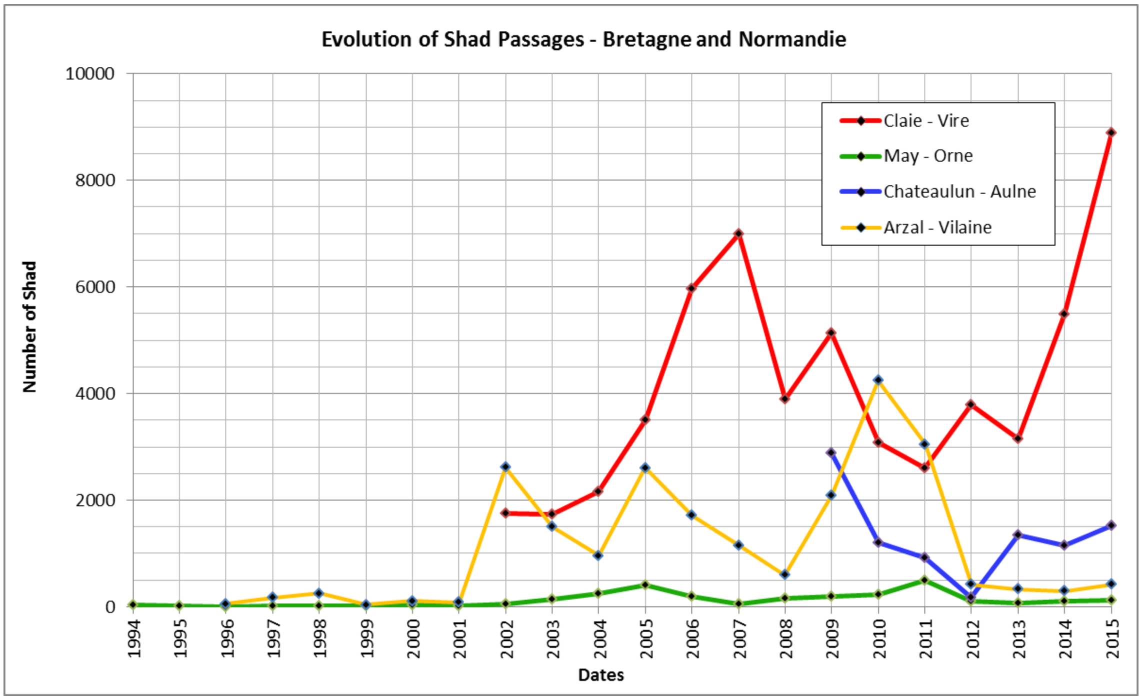

Figure 3-7 Evolution of Shad Passages in Bretagne and Normandie (1994 to 2015).

3.2 PERIOD, FLOW, AND TEMPERATURE

At Holyoke, on the Connecticut River, migrations mainly happen in May, for a 30 to 40-day period. Migrations occur for average flows corresponding to 120 to 150% of the watercourse mean annual discharge. Preferential water temperatures range from 16 to 21°C (Leggett & *al.*, 1972).

At Lawrence, on the Merrimack River, analyses revealed results which are quite similar to those observed at Holyoke: most of the migrations occur in May, over a period of about 40 days, in flows corresponding to the watercourse mean annual discharge. The majority of passages happen in water temperatures ranging from 13/14 to 21°C at Lowell (Sprankle, 2005).

On the Susquehanna River, the observations are very similar to those on the two previous watercourses. The majority of migrations occur in May, for a period of 30 to 40 days, during which flows represent, on average, 130 to 140% of the mean annual discharge. Water temperatures range from 13/14 to 21°C (Normandeau and Gomez and Sullivan, 2011; Normandeau and Gomez and Sullivan, 2012).

Table 3-3 Shad Migration Rates at the First Downstream Dams: Holyoke (Connecticut), Lawrence (Merrimack) and Conowingo (Susquehanna).

River	Period	Average Number	Migration Period	Migration (5% - 95%)		
				Period	Number of Days	Average Flow (m^3/s) and (% Mean Annual Discharge)
Susquehanna (Conowingo)	2002-2015	47,439	April - Mid-July	Mid-April - 3rd week of May	36	1,630 (140%)
	2003 (max)	125,135	Mid-April - 1st week of June	4th week of April - 3rd week of May	30	1,515 (130%)
Merrimack (Lawrence)	1983-1996	11,448	May - July	May 14 - June 24	42	258 (114%)
	1992 (max)	20,796	May 9 - July 31	May 15 - June 22	39	223 (99%)
Connecticut (Holyoke)	1983-1992	439,816	April - August	May 5 - June16	43	658 (134%)
	2012-2015	416,640	April - July	May 5 - June 6	33	737 (150%)
	1992 (max)	721,764	April - July	May 9 - June 5	28	595 (121%)

On the Columbia River (West Coast), as on the East Coast, the time window for shad migration is narrow. During the last decade (2006 - 2015), during which more than 22 million shad migrated upstream of the Bonneville dam, 90% (5% - 95%) of them passed through the fishway over a 40- to 50-day period depending on the year, mostly in June (see Figure 3-8). Based on data taken from http://www.cbr.washington.edu/dart/, it appears that the vast majority of passages occur in flows corresponding to 90 to 210% of the mean annual discharge and in water temperatures between 14 and 19.5°C. This latter result is similar to what Leggett & *al.* (1972) stated.

In Europe, results are generally fairly similar to those observed for the American shad. Their migrations are short-lived when they reach the obstacles; the majority of the passages at various sites occur over a maximum period of 40 to 50 days.

Table 3-4 Migration Rates of Shad at the Main Monitoring Stations in France.

Watercourse	Obstacle	Year of Monitoring	90% Passage
Claies de Vire	Vire	2002 - 2015	End of April to end of May
Orne	Feuguerolles - Bully	1994 - 2015	Mid-April to Mid-May
Seine	Poses	2008 - 2012	--
Vilaine	Arzal	1996 - 2015	April to Mid-May
Aulne	Chateaulin	2009 - 2015	Mid-April to Mid-May
Vienne	Chatellerault	2004 - 2015	End of April to Mid-June
Creuse	Descartes	2007 - 2015	Mid-April to Mid-June
Loire	Decize	1998 - 2015	Mid-April to end of May
Allier	Vichy	1998 - 2015	May to early June
Charente	Crouin[1]	2010 - 2015	May to Mid-June
Garonne	Golfech	1987 - 2015	May to June
Garonne	Bazacle	1993 - 2015	Mid-May to Mid-July
Dordogne	Tuilières	1989 - 2015	May to June
Dordogne	Mauzac	1992 - 2015	Mid-May to June
Pau	Puyoo	1996 - 2002	April to May

1 Passages correspond to Allis shad (Alosaalosa) and Twait shad *(Alosafallax)*.

For instance, Figure 3-9, Figure 3-10 and Figure 3-11 present the annual migration rate at the Descartes (on the Creuse), Châtellerault (on the Vienne), and Arzal (on the Vilaine) dams (Bach & *al*., 2015; Briand & *al*., 2015).

At the Tuilières (on the Dordogne) and Golfech (on the Garonne) dams, a summary of the data collected from 1989 - 1999 (Chanseau & *al*., 2000) shows that migrations mainly occur at the three sites when the water temperatures range from 13 - 14 to 21 - 22°C. Regardless of the site, the majority of passages are observed in flows ranging from the mean annual discharge, to twice that discharge at the right of the structures.

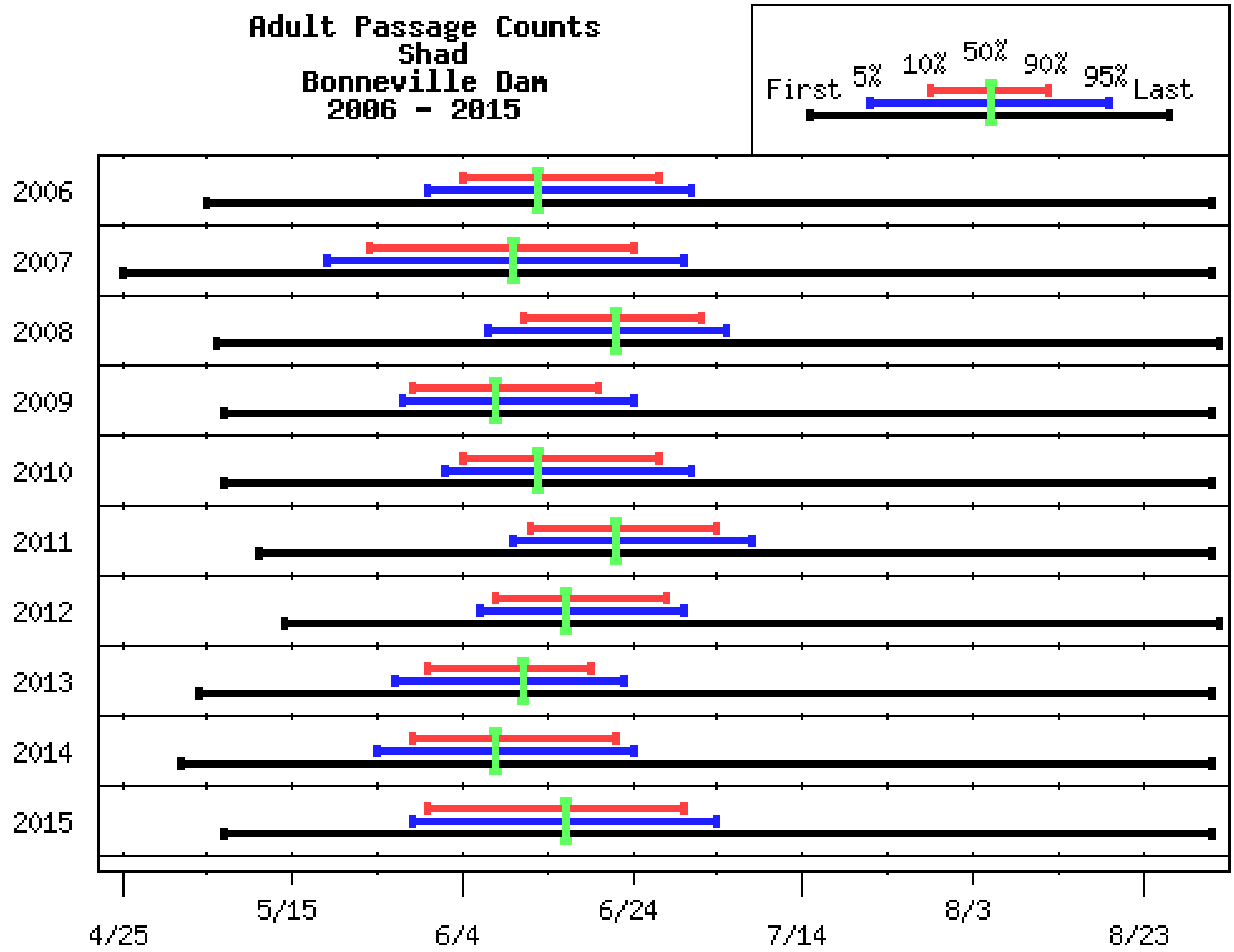

Figure 3-8 Migration Rates of Shad from 2006 to 2015 at the Bonneville Dam on the Columbia River (source: http://www.cbr.washington.edu/dart/).

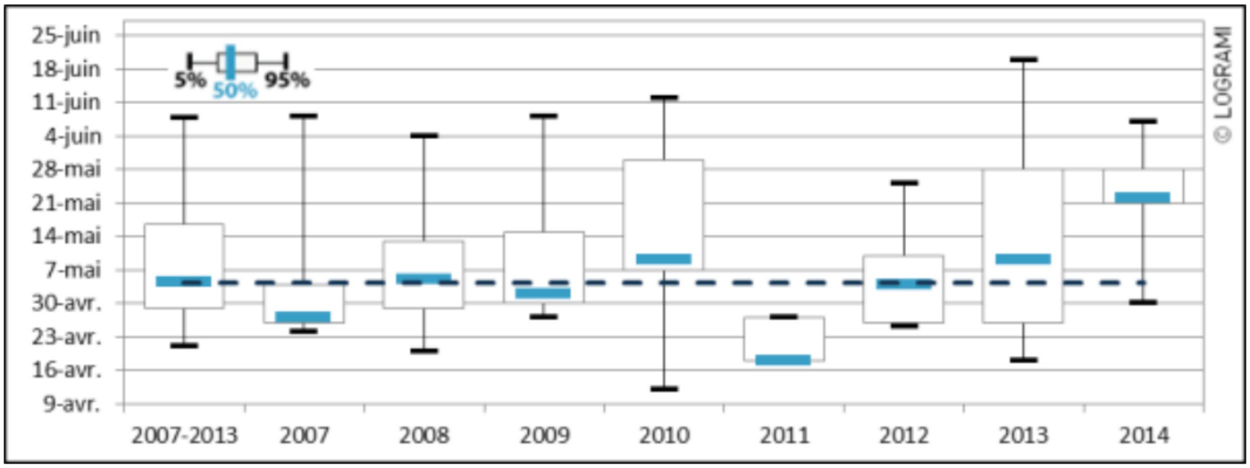

Figure 3-9 **Migration Rates from 2007 to 2014 at the Descartes Dam on the Creuse River (France) (Bach et *al*., 2015).**

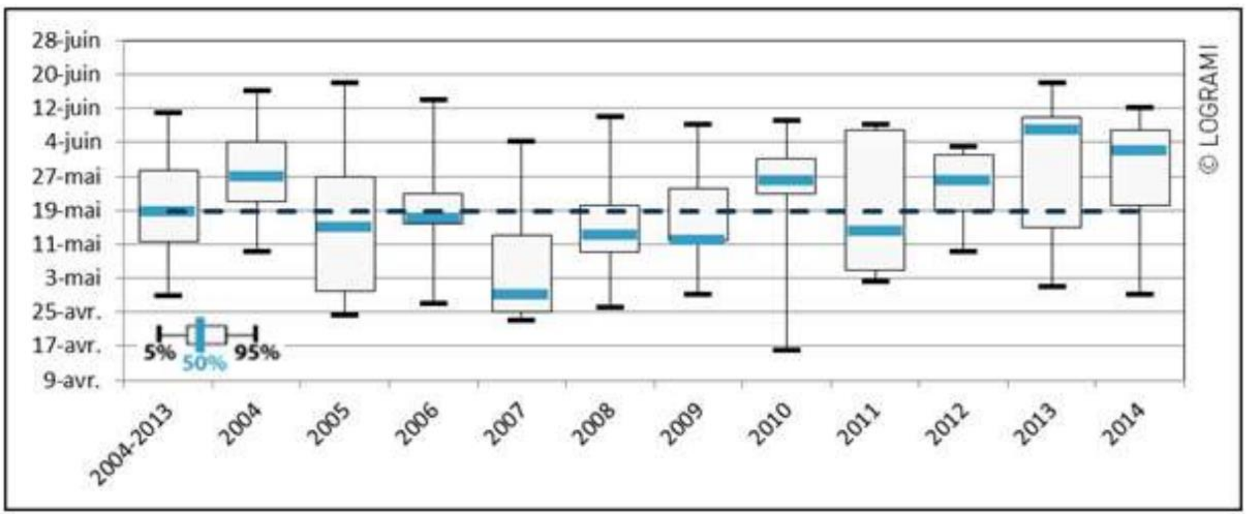

Figure 3-10 **Migration Rates from 2004 to 2014 at the Châtellerault Dam on the Vienne River (France) (Bach et *al*., 2015).**

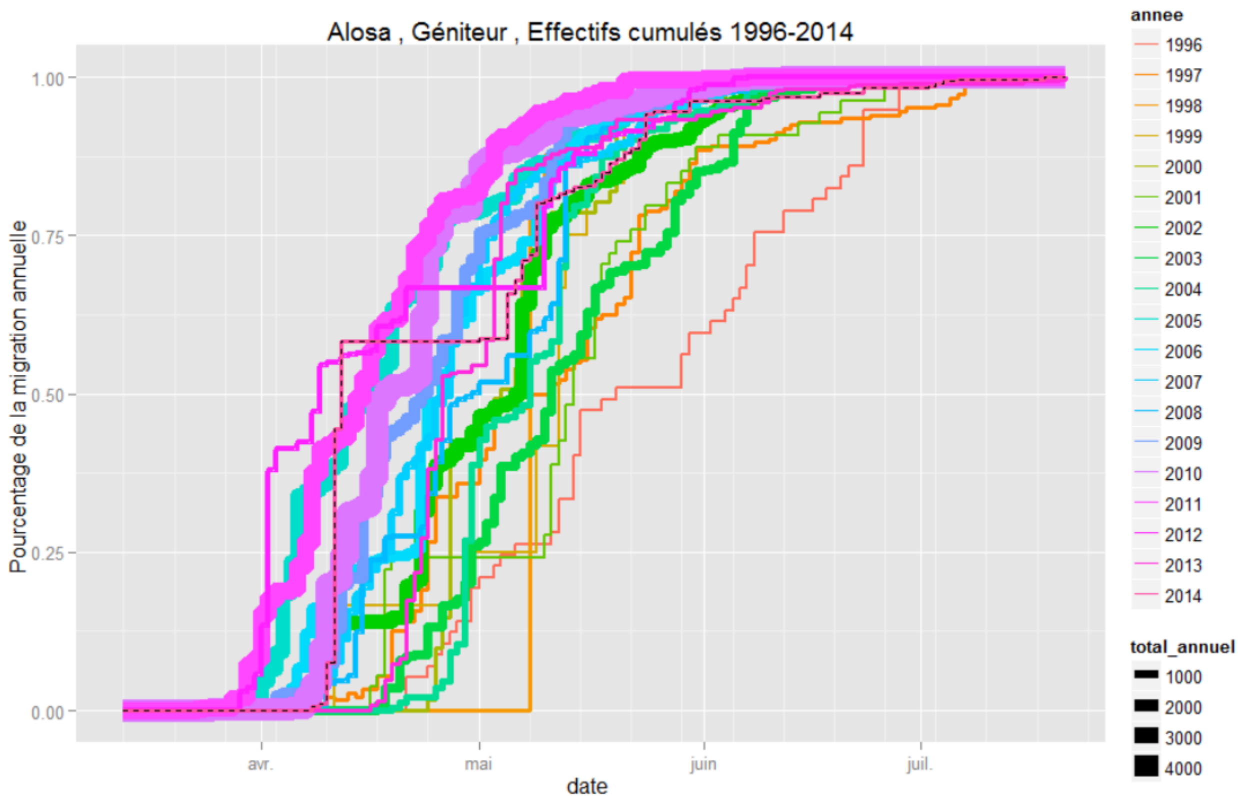

Figure 3-11 **Migration Rates from 1996 to 2014 at the Arzal Dam on the Vilaine River (France) (Briand et *al*., 2015).**

4 SYNTHESIS OF KNOWLEDGE ON THE EFFICIENCY OF FISHWAYS

4.1 CONCEPT OF EFFICIENCY OF A FISHWAY

The efficiency of fishways is divided into three major steps:

- → ***Remote attraction***, i.e., the fish's ability to enter the area influenced by the flows from the fishway, near the entrance(s). It is quantified by calculating the percentage of fish that come into the area in relation to the total number of fish migrating at the foot of the structure. This "remote" attraction largely depends on the configuration of the structure, the number and the location of entrances in relation to the hydraulic conditions downstream of the development as well as the fishway's supply flow.

- → ***Close attraction***, i.e., the ability of fish within the fishways' area of influence to enter said fishway. It is quantified by calculating the percentage of fish entering the fishway in relation to the number of fish within the fishway's area of influence. It depends notably on the hydraulic conditions near the entrances (fish ladder supply flow, form of streams, hydraulic conditions directly), the dimensions of the entrances, changing light levels, etc.

The ***total attraction*** of the fishway encompasses the remote and close attraction and can be quantified by determining the percentage of fish that entered the fishway in relation to the total number of fish immediately downstream from the structure. It shows the potential maximum efficiency of the fishways, in so far as the fish can only overcome the structures by entering the fishways (no fish in, no fish out).

- → ***Passability*** of the fishway, i.e., the fish's ability to pass through the entire fishway after entering it. This can be quantified by determining the percentage of fish that have passed to the upstream side of the structure in relation to the number of fish that entered the fishway.

The ***effectiveness*** of the fishway, resulting from the three elements presented above, can be qualified by determining the proportion of fish who pass to the upstream side in relation to the individuals present at the foot of the structure.

Only monitoring using telemetry provides complete information. However, the data available in the documents consulted did not allow for detailed analyses taking into account the individual behaviour of each fish, which would have provided a richer pool of knowledge.

4.2 MONITORING TECHNIQUES

Information on the various steps presented above can be provided thanks to various techniques.

FISH COUNTS IN FISHWAYS

Fish counts help better understand the fish diversity in the watercourses, determine and monitor the evolution of populations and the biometric characteristics of the species crossing the structures, as well as understand the impact of environmental conditions on migration. Fish counts alone cannot be used to determine the efficiency of the fishway, nor the blocking time and the issues encountered by fish in order to cross the structures. However, when several obstacles are erected along the same migration route and within short distances from one another and when said obstacles have each a counting station, it is possible to determine the ***transfer rate*** of fish between the downstream and the upstream structure. It is then possible to assess the cumulative impacts of the various structures and to identify, at times, dysfunctions of certain fishways. These **transfer rates correspond to the minimum efficiency** of fishways, meaning that all fish having crossed the downstream structure appear at the upstream obstacle and try to overcome it. This is not always true and depends on various parameters, such as the distance between the structures, the presence of spawning areas or of a tributary between the dams, the environmental conditions, etc. By the same reasoning, the cumulative impacts of the various structures erected along a same migration route correspond to maximum values when systematically assuming that fish reproducing downstream of the dams previously tried to cross them. It is interesting to determine the transfer rate by double-counting, since it allows for the collection of information each year and on multiple species at once.

The Table 4-1 presents the transfer rate between the various dams on the Connecticut, Merrimack and Susquehanna rivers.

Table 4-1 Shad Transfer Rate between the Various Dams on the Susquehanna, Merrimack and Connecticut Rivers, U.S. East Coast.

River	Section	Distance between Dams (km)	Period	Transfer Rate (%)			
				Average	1st Quartile	Median	3rd Quartile
Connecticut	Holyoke - Turners Falls (Cabot + Gate House or Spillway + Gate House)	59	1983 - 2015	4.7	1.4	3.3	7.2
	Turners Falls - Vernon	30	1983 - 2015	36.9	8.0	31.0	66.0
Merrimack	Lawrence - Lowell	22	1989 - 2015	14.7	9.5	11.6	18.0
Susquehanna	Conowingo - Holtwood	23	1997 - 2015	31.1	19.2	27.5	46.6
	Holtwood - Safe Harbor	11	1997 - 2015	69.1	66.4	72.3	74.0
	Safe Harbor – York Haven	38	2000 - 2015	9.2	2.4	7.3	11.2

Table 4-2 presents the transfer rates between the structures on the Columbia River. As a comparison, the mean transfer rates (1st quartile / median / 3rd quartile) of chinook salmon between The Dalles and John Day; and between John Day and Mc Nary for the same period 1968-2003 are 79.4% (76.7% / 78.3% / 82.1%) and 88.8% (84.1% / 87.8% / 95.5%), respectively. This clearly illustrates the main difficulties in ensuring a high efficiency of shad fishways compared to salmon.

Table 4-2 Shad Transfer Rate between The Dalles, John Day and Mc Nary Structures on the Columbia River, U.S. West Coast.

River	Section	Distance between the Structures (km)	Period	Transfer Rate (%)			
				Average	1st Quartile	Median	3rd Quartile
Columbia	The Dalles – John Day	23	1968 - 2003	52.4	46.0	52.5	57.7
	John Day – Mc Nary	11	1968 - 2003	51.4	37.6	48.2	60.6

For the European shad, only on the Dordogne axis can the transfer rates between two structures, namely between Tuilières and Mauzac, be determined based on annual counts in the fishways. The structures are only separated by some 15 km and there are no major tributaries (Table 4-3).

Table 4-3 Shad Transfer Rates between the Various Structures of the Dordogne River, France.

River	Section	Distance between the structures (km)	Period	Transfer Rate (%)			
				Average	1er quartile	Médiane	3e quartile
Dordogne	Tuilières – Mauzac	15	1992 - 2015	14.0	1.6	7.8	19.0

MONITORING USING RADIO OR ACOUSTIC TELEMETRY

This monitoring consists in equipping fish with active transmitters (i.e., equipped with a battery) and to monitor their movements with fixed or mobile antennas. The receiving range can reach several hundred metres, but monitoring is time-limited due to battery life. This helps for the precise study of fish behaviour around dams, near and in the fishways, and in determining the time spent downstream of the obstacles, blockage periods and the efficiency of the fishways (provided that there is a sufficient number of fish monitored). However, the biases related to the capture and marking of fish can be significant. For example, Castro-Santos et *al*. (2014) highlighted that the passability rate of American shad at the Gate House plant at Turner Falls on the Connecticut River, determined by telemetry, was clearly lower than the rate observed by comparison of the passages recorded in the Cabot Plant and Gate House fishways. There are, however, other telemetry studies on the American shad which show efficiency results similar to the transfer rates (Vernon in 2011; Holtwood in 2001 and 2008). For the European shad, the null efficiencies observed at the Tuilières (Dordogne River) and the Golfech (Garonne River) fishways, which are based on a very limited number of marked fish, do not reflect the reality. Indeed, these fishways allowed the passage of tens of thousands of fish some years. In general, results concerning the overall efficiency of the structures obtained through telemetry monitoring should be analysed with caution. This technique however does help identify the problems encountered by fish at dams, especially with respect to the ***remote and close attraction and the passability of fishways***. Various studies have been carried out on the American shad on the U.S. East Coast. The main fishway results are presented in Table 4-4.

MONITORING USING RADIO-FREQUENCY IDENTIFICATION TECHNOLOGY (RFID)

Unlike radio or acoustic telemetry, RFID monitoring uses passive transmitters which use the energy of antennas to emit their code. This is why the detection ranges are short (up to about 1 m), but also allow fish to be monitored over very long periods (up to 15 years). It cannot determine the general behaviour of fish around the structures, nor the overall efficiency of fishways or the duration of blockages. However, it provides information in addition to the telemetric data (radio or acoustic) obtained at fishways: number of entrances into the fishways, behaviour inside should there be several detection systems installed, duration of passage, % of fish entering the fishway and reaching the upstream side, etc. The lower monitoring cost generally allows for the marking of far more fish and produces more robust results. Moreover, fish marking is easier and seems less traumatic than radio or acoustic telemetry. The data available on the shad, presented in Table 4-5, refer almost exclusively to the three fishways at the Turner Falls site on the Connecticut (Cabot Hydroelectric Station, spillway and Gate House).

Table 4-4 Summary of the Various Studies Carried out Using the Radio Telemetry in Order to Define the Behaviour of Shad and the Impacts of Dams.

River	Sites (year)	Reference	Type of fishway	Remote Attraction	Close Attraction	"Total" Attraction	Overcoming the Fish Ladder	Overall Effectiveness
Susquehanna (USA)	Conowingo (2010)	Normandeau and Gomez and Sullivan, 2011	Lift	90% (n = 80)	81% (n = 65)	73%	62% (n = 40)	45%
Susquehanna (USA)	Conowingo (2012)	Normandeau and Gomez and Sullivan, 2012	Lift	64% (n = 42)	69% (n = 29)	44%	59% (n=17)	26%
Susquehanna (USA)	Holtwood (2008)	Normandeau and Gomez and Sullivan, 2011	Lift	--	--	75% (n = 96)	15% (n = 14)	11%
Susquehanna (USA)	Holtwood (2010)	Tryninewski & Hendricks, 2012	Lift	--	--	63% (n = 86)	53% (n = 46)	34%
Susquehanna (USA)	York Haven (2010) [1]	York Haven Power Company; LLC, 2011	Fish ladder (slots + serpentine)	82% (n = 28)	32% (n = 9)	26%	56% (n = 5)	15%
Connecticut (USA)	Holyoke (1980)	Barry & Kynard, 1982	Fish lift[2]	--	--	--	--	42% (n = 5)
Connecticut (USA)	Holyoke (1981)	Barry & Kynard, 1982	Lift	--	--	--	--	67% (n = 4)
Connecticut (USA)	Holyoke (2011)	Sprankle, 2012	Lift	--	--	--	--	65% (n = 35)
Connecticut (USA)	Turners Falls - Gate House (2008)	Castro Santos & Haro, 2014	Fish ladder (slots) with collecting canal	--	--	51% (n = 19)	47% (n = 9)	24%
Connecticut (USA)	Turners Falls - Gate House (2009)	Castro Santos & Haro, 2014	Fish ladder (slots) with collecting canal	--	--	14% (n = 6)	50% (n = 3)	7%
Connecticut (USA)	Turners Falls - Gate House (2009) [3]	Castro Santos & Haro, 2014	Fish ladder (slots) with collecting canal	--	--	36% (n = 5)	60% (n = 3)	21%
Connecticut (USA)	Turners Falls - Gate House (2010)	Castro Santos & Haro, 2014	Fish ladder (slots) with collecting canal	--	--	47% (n = 18)	50% (n = 9)	24%
Connecticut (USA)	Turners Falls - Gate House (2010) [3]	Castro Santos & Haro, 2014	Fish ladder (slots) with collecting canal	--	--	98% (n = 45)	27% (n = 12)	26%
Connecticut (USA)	Vernon	Castro Santos, 2011	Fish ladder (Ice Harbor)	58% (n = 19)	42% (n = 8)	24%	0%	0%

River	Sites (year)	Reference	Type of fishway	Remote Attraction	Close Attraction	"Total" Attraction	Overcoming the Fish Ladder	Overall Effectiveness
Merrimack (USA)	Lawrence (1993)	Lawrence Hydroelectric Project, 2013	Lift	--	--	--	30%	--
Merrimack (USA)	Lawrence (1994 - 1995)	Lawrence Hydroelectric Project, 2013	Lift	--	--	--	72%	--
Merrimack (USA)	Lowell (Pawtucket)	Sprankle, 2005	Lift	50% (n = 18)	--	--	--	11% (n = 4)
Merrimack (USA)	Lowell (Pawtucket)	ALDEN, 2011	Lift	--	--	11% (n = 3)	67% (n = 2)	7%
Cooper (USA)	Pinopolis Lock (2002)	Normandeau Associates Inc., 2003	Lock	85% (n = 74)	66% (n = 49)	56%	90% (n = 44)	51%
Cooper (USA)	Pinopolis Lock (2003)	Normandeau Associates Inc., 2003	Lock	86% (n=82)	92% (n=75)	79%	96% (n=72)	76%
Cape Fear (USA)	Locks and Dams 1 (1996)	Moser et al., 2000	Lock	--	--	75% (n = 12)	33% (n = 4)	25%
Cape Fear (USA)	Locks and Dams 1 (1997)	Moser & al., 2000	Lock	--	--	55% (n = 6)	33% (n = 2)	18%
Cape Fear (USA)	Locks and Dams 1 (1998)	Moser & al., 2000	Lock	--	--	83% (n = 30)	60% (n = 18)	50% [4]
Cape Fear (USA)	Locks and Dams 1, 2, 3 (2008)	Smith & Hightower, 2012	Locks	--	--	--	--	65% (n = 13) à LD1 85% (n = 11) à LD2 64% (n = 7) à LD3
Dordogne (France)	Bergerac	Verdeyroux & al., 2016	Fish ladder (slots)	100% (n = 4)	50% (n = 2)	50% (n =2)	50% (n = 1)	25%
Dordogne (France)	Tuilières	Verdeyroux & al., 2016	Lift	88% (n = 7)	0%	0%	-	0%
Garonne (France)	Golfech	Verdeyroux & al., 2016	Lift	100% (n = 5)	80% (n = 4)	80% (n = 4)	0%	0%

1 The fishway is located in an inlet of the Susquehanna, which is supplied by a minimum flow of 56 m/s^3.
2 All fish swam up the tailrace.
3 Fish carried all the way from Holyoke and released in the channel upstream of the Cabot Hydroelectric Station.
4 Three fish swam through a Denil fishway and the weir. In the end, the passability rate of the structure is 61%.

Table 4-5 Summary of the Various Studies Carried out Using the RFID Technology in Order to Define the Behaviour of Shad near the Fishways.

RIVER	SITES (YEAR)	REFERENCE	TYPE OF FISHWAY	PASSABILITY	MEDIAN TRANSIT TIME IN THE FISHWAY (H)	MEDIAN TIME PER LADDER (MIN)
Connecticut (USA)	Turners Falls Cabot Plant (1999)	Haro & *al.*, 1999	Fish ladder (Ice Harbor)	18% (n = 19)	24.6	22.4
Connecticut (USA)	Turners Falls Cabot Plant (2000)	Haro & *al.*, 2001	Fish ladder (Ice Harbor)	17% (n = 26)	8.3	7.5
Connecticut (USA)	Turners Falls Cabot Plant (2001)	Sullivan & al., 2002	Fish ladder (Ice Harbor)	16% (n = 67)	5.6	5.1
Connecticut (USA)	Turners Falls Cabot Plant (2011)	Castro-Santos & Haro, 2014	Fish ladder (Ice Harbor)	34% (n =11), but 63% for multiple spawners	--	--
Connecticut (USA)	Turners Falls Cabot Plant (2012)	Castro-Santos & Haro, 2014	Fish ladder (Ice Harbor)	18.5% (n = 5)	--	--
Connecticut (USA)	Turners Falls Spillway (1999)	Haro & *al.*, 1999	Fish ladder (Ice Harbor)	14% (n = 7)	4.5	7.7
Connecticut (USA)	Turners Falls Spillway(2000)	Haro & *al.*, 2001	Fish ladder (Ice Harbor)	8% (n = 6)	6.4	11
Connecticut (USA)	Turners Falls Spillway(2001)	Sullivan & al., 2002	Fish ladder (slots)	32% (n = 24)	6.9	11.8
Connecticut (USA)	Turners Falls Spillway (2012)	Castro-Santos & Haro, 2014	Fish ladder (Ice Harbor)	8% (n =1)	--	
Connecticut (USA)	Turners Falls Gate House (1999)	Haro & *al.*, 1999	Fish ladder (slots)	88% (n = 80)	< 10 min.	Few dozen seconds (max.)
Connecticut (USA)	Turners Falls Gate House (2000)	Haro & *al.*, 2001	Fish ladder (slots)	81% (n = 59)	< 2 min	Few dozen seconds
Connecticut (USA)	Turners Fall Gate House (2001)	Sullivan & al., 2002	Fish ladder (Ice Harbor)	84% (n = 180)	< 2 min.	Few dozen seconds (max.)
Connecticut (USA)	Turners Falls Gate House (2012)	Castro-Santos & Haro, 2014	Fish ladder (Ice Harbor)	87% (n = 91)	< 2 min.	Few dozen seconds (max.)
Connecticut (USA)	Vernon (2011)	Castro-Santos, 2011	Fish ladder (Ice Harbor)	0% (n = 18)	--	--
Dordogne (France)	Mauzac (2005)	Chanseau & *al.*, 2006	Fish ladder (slots)	60% (n = 3)	--	Average of 11 s.

4.3 OVERALL EFFICIENCY

4.3.1 U.S. EAST COAST

THE CONNECTICUT RIVER

The three sites monitored by telemetry are Holyoke (KM 139), Turners Falls (KM 198) and Vernon (KM 228). The following efficiency was observed (see Table 4-4):

- Holyoke: 42% in 1980, 67% in 1981 and 65% in 2011;
- Turners Falls (Gate House): from 7 to 26% between 2008 and 2010;
- Vernon: no shad were able to cross the structure during the 2011 monitoring campaign (dysfunction of the fishway that year).

Video monitoring (see Table 4-1) shows average ***transfer rates*** between the Holyoke and Turner Falls dams (Gate House) and between Turner Falls (sequence of two fishways: Cabot + Gate House or Spillway + Gate House) of 4.7% (min: 0.6%; max: 14.1%). It illustrates the long-established significant problems related to the passability of the Turners Falls structure, in relation with the selection of the Ice Harbor-type fish ladder installed on the Cabot Hydroelectric Station and the spillway (see Haro. & *al*., 1999; Sullivan & *al*., 2002).

The transfer rates observed between Turners Falls (Gate House) and Vernon raises questions. They appear to be very high certain years and in 1996 and 2001, the number of passages observed at Vernon was even greater than the passages at Gate House. The explanation could lie with the counting, done manually up to 2006. If we only take into consideration the 2007-2011 period, the mean transfer rate is 2.4%. In 2011, several problems were highlighted: damaged weir in the lower part of the fishway, unsuitable flows at certain weirs, lack of regulation of the fall at the fish entrance. Improvement work was carried out before the 2012 migration, thus greatly increasing the efficiency of the fishway (see Figure 3-1 and Table 4-1). The transfer rate observed in recent years is on average 57% (min: 38.9%; max: 69.4%).

On average, only 2% of shad monitored at Holyoke (maximum of 10%) manage to proceed upstream of Vernon, the third structure located 89 km upstream from the first.

In 2015, for the first time, 44 shad were observed at Bellow Falls, the 4th structure of the axis, located 280 km from the ocean, i.e., about 50 km upstream of Vernon.

The number of fish counted at the structures located downstream does not seem to influence the transfer rates of those upstream. Similarly, the impact of the flows is not apparent even if the transfer rates seem low during years with high hydrology in May, which is the main migratory period. This could be explained by a lower fishway attraction compared to other higher flows (turbinated and discharged flow).

At Holyoke, average blocking duration ranges from 2 to 5 days at the plant and 6 to 7 days at the dam.

At the Vernon structure in 2011, fish were present directly downstream of the site for up to 30 days, though the majority stayed less than 20 days.

Results obtained at the various sites also highlighted that the passability of Ice Harbor-type fishways is significantly lower than the slot fishway at Gate House.

THE MERRIMACK RIVER

The Lawrence (KM 48) and Lowell (KM 70) dams are 22 km apart. ***Overall efficiencies*** at Lowell of 11% in 2002 and 7% in 2011 were determined through telemetry monitoring (see Table 4-4).

Video monitoring (see Table 4-1) showed an average ***transfer rate*** of 14.7% between the two dams (min: 2.7%; max: 37.9%). The number of fish counted at the Lawrence structure does not seem to influence the passages at Lowell. The low design flow of the Lowell hydroelectric plant (215 m^3/s), compared to the hydrology of the watercourse (average of 550 m^3/s during the month of May) and the presence of a watercourse segment at the end of which a fish ladder with two vertical slots (without a counting station) is installed, means that the transfer rate cannot always be properly recorded. It is worth noting that the best transfer rate (38%) was observed during the only year without spillway discharge during the month of May (1995).

In 1993, at Lawrence, fish were blocked for an average of 5 days.

THE SUSQUEHANNA RIVER

On the Susquehanna River, telemetry monitoring (see Table 4-4) conducted at the three structures of Conowingo (KM 16), Holtwood (KM 39) and York Haven (KM 88) helped determine the following overall efficiency:

- Conowingo: 45% in 2010 and 26% in 2012;
- Holtwood: 34% in 2001 and 11% in 2008;
- York Haven: 15% in 2010,

Video monitoring (see Table 4-1) shows average ***transfer rates*** of 31.1% between Conowingo and Holtwood (min: 0.1%; max: 63.4%), 69.1% between Holtwood and Safe Harbor (min: 38.1%; max: 98.4%) and 9.2% between Safe Harbor and York Haven (min: 0.0%; max: 22.2%). The presence of significant spawning areas downstream of York Haven partly explains the low transfer rates at this site (C. Freese, pers. com., 2015). The transfer rate between Holtwood and Safe Harbor represents the maximum observed on the three watercourses studied.

The number of fish counted at the structures does not seem to have an influence on the transfer rate at the upstream structures.

A cross-sectional analysis of the average flow in May at Conowingo and of the transfer rates between Conowingo and Holtwood as well as between Holtwood and Safe Harbor, helps highlight that the hydrology of the watercourse, which prepares the plant operations, the attraction of fishways and dam outfall, all have an impact on the transfer rates which tend to decrease as flow increases (Figure 4-1).

At Conowingo, fish were blocked, on average, 4 days 20 hours and 9 days 4 hours in 2010 and 2012, respectively.

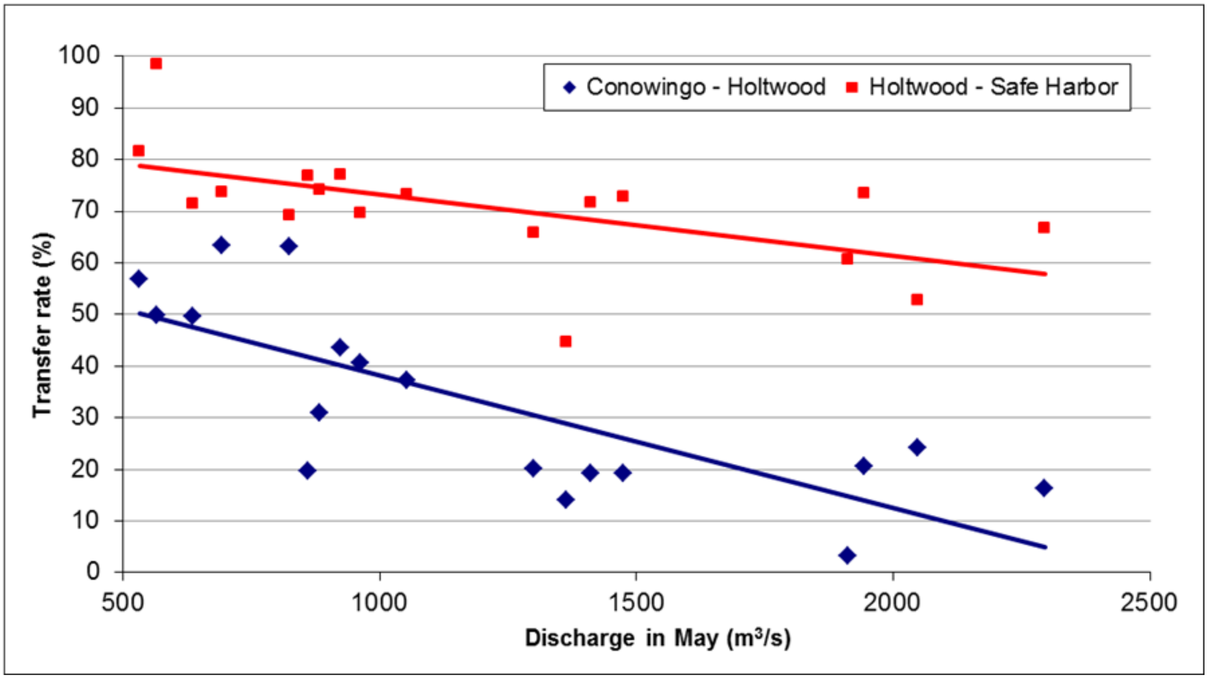

Figure 4-1 **Transfer Rate between the Conowingo and Holtwood Structures, and the Holtwood and Safe Harbor Structures on the Susquehanna River Depending on the Average Flow in May.**

THE CASE OF SAFE HARBOR ON THE SUSQUEHANNA RIVER (UNITED STATES)

Safe Harbor was an interesting case to study in greater detail. Out of all the sites studies, it appeared to be the one which had the smallest impact on shad migration, with a transfer rate from Holtwood of nearly 70% on average which varies only slightly from one year to the next (1^{st} quartile = 66.4%; 3^{rd} quartile = 74%). This result might seem surprising particularly when taking into account the size of the hydroelectric development (plant more than 300 m in width) and the high turbinated flow (3,100 m^3/s). The fishway is made up of a lift on the right bank of the plant which is supplied by a total flow of 17 m^3/s, i.e., about 0.55% of the maximum turbinated flow (3,100 m^3/s) and about 1.36% of the average flow in May (1,245 m^3/s; main migration period).

This lift has three entrances: the first, which consists of the main entrance, is located about 75 m downstream of the plant, in the flow lines of the units; the second, now condemned, located directly downstream of the turbines, with a stream perpendicular to the discharge; and the third, at the foot of the plant, upstream of the restoration of the units (i.e., above the draft tubes) with a stream perpendicular to the discharge. The lift only works during the day and its ascending cycle during migration peaks is 25-30 min. The two turbines located near the lift are the last to be started in order to prevent disturbance of the fishway attraction (R. Wagner, pers. com. 2015).

Besides the fact that the plant is highly equipped compared to the hydrology of the watercourse, which makes it very attractive for fish and limits the risk of attraction to the dam caused by discharges, the main difference with other sites is the presence of an entrance to the fishway at the foot of the plant, above the units draft tubes, in a relatively calm area by a hydraulic point of view, allowing the stream to propagate over a long distance. To date, no study has been carried out to verify that this entrance is in fact widely used by shad.

4.3.2 U.S. EAST COAST – COLUMBIA RIVER

A summary analysis of passages counted at the various structures of the downstream Columbia River was carried out.

However, the results must be considered with care since it is impossible to determine the number of fish passing through the locks, number which is *a priori* low (Noyes, 2013) and the uncertainty concerning counting when there are a lot of fish passing through the fishways. Some years, the numbers of monitored fish in fishways of downstream obstacles are clearly lower than the numbers observed at the upstream obstacles, which translates to **transfer rates** that are greater than 100%.

From 1968 to 2003, for which passage records exist, the average **transfer rates** between The Dalles (KM 308) and John Day (KM 347) structures and the Johh Day and Mc Nary (KM 470) structures are 51.9% and 50.0%, respectively, which translates to an average passage at Mc Nary of 27% (min: 11.4%; max: 57.9% of shad monitored at The Dalles).

An analysis comparing the average flows in June (main migration period) and the transfer rate between the John Day and Mc Nary structures highlights the strong influence of the watercourse hydrology (Figure 4-1): the greater the June flows are, the weaker the transfer rate is.

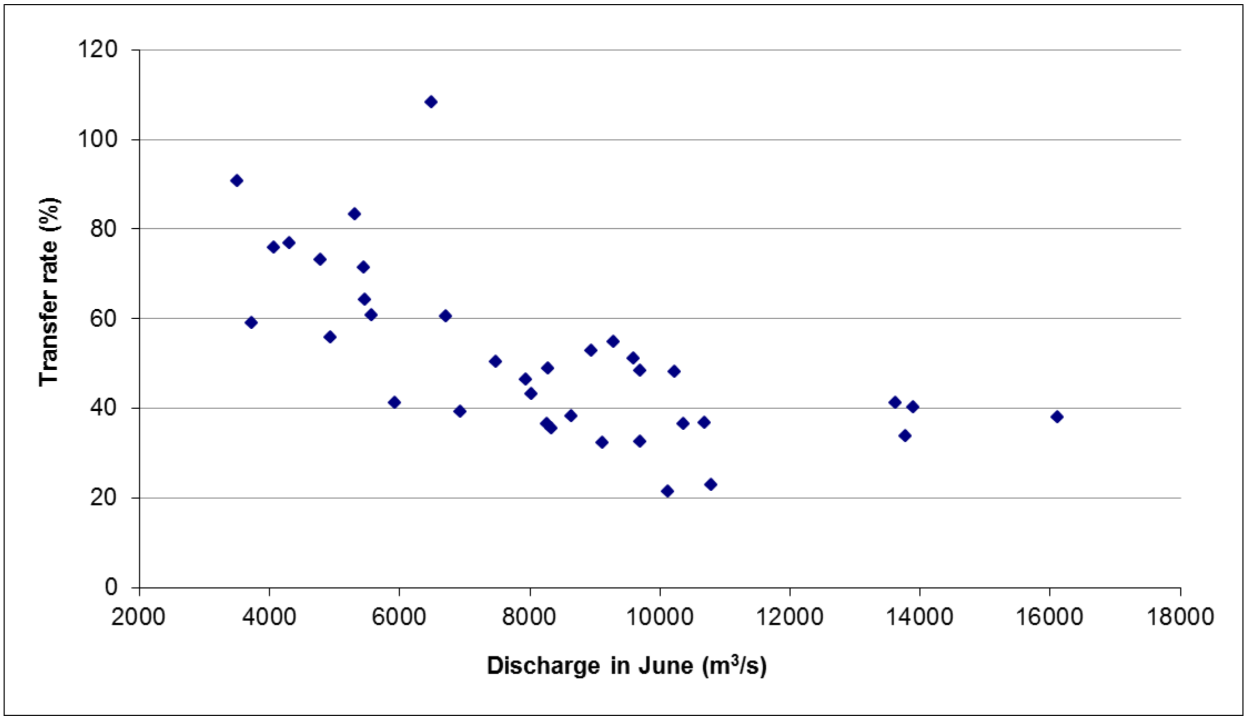

Figure 4-2 Transfer Rate between the John Day and Mc Nary Structures on the Columbia River in Relation to the Average Flow in June (1968 - 2003).

4.3.3 FRANCE – GARONNE AND DORDOGNE RIVERS

Although telemetry monitoring was performed on the Garonne (Golfech) and Dordogne (Bergerac and Tuilières) structures, the **overall efficiency** of these hydroelectric developments could not be assessed because of the very low number of fish that appeared downstream of the obstacles (Verdeyroux & *al*. 2015).

On the Dordogne, thanks to the video counting at the Tuilières fishway and the monitoring of reproduction downstream of the two structures, the following global **transfer rates** for the 2003-2015 period can be proposed: between 55 and 65% at Bergerac, and between 35 and 55% at Tuilières (in accordance with the hypotheses considered for the assessment of the spawning stocks) (Courret & Chanseau, 2015).

Video monitoring at Tuilières and Mauzac showed a marked evolution over time of the **transfer rates** between the two dams. They were around 40% on average for the 1993-1996 period, when the fishway operated correctly and the hydroelectric plant's operation was optimised for the passage of fish (between 35,704 and 87,254 [approx.] shad going through Tuilières). Since the early 2000s, rates have varied depending on the year from 5% to 15%. It is also possible given the marked school behaviour of the species and the low number of fish observed at the Tuilières station over the last few years (from a few dozen to 5,635 shad since 2009) that the shad are less inclined to continue their migration upstream, which can have an influence on the transfer rate at Mauzac.

Over the last few years, only a small percentage of fish appearing at Bergerac reached upstream from Mauzac.

On the Garonne, the comparison between the spawning stock reproducing on the spawning ground located directly downstream of Golfech and the others which cross the structure, allows us to propose a lift efficiency of between 50 and 65% (Chanseau & *al.*, 2000). However, it is likely that this represents a maximum efficiency, i.e., the fish in other spawning grounds, located a few kilometres downstream, were not taken into account.

4.4 MAIN DIFFICULTIES ENCOUNTERED BY SHAD

The monitoring conducted on the various sites, with Table 4-2 and Table 4-3 presenting the overall results, was used to characterise fish behaviour at the structures and to identify the main difficulties that they encounter.

4.4.1 FINDING THE ENTRANCES AND ENTERING THE FISHWAYS

The <u>first difficulty</u> for fish is to arrive near the fishway entrances. This is directly linked to the number of fishways available and their location on the structure, based notably on the downstream hydraulic conditions.

With the exception of Golfech and Bergerac for which monitored fish numbers are very low, there is no site where all fish come close to the fishway entrances. The **remote attraction** varies between 50 and 90%. This is most likely due to the fact that the shad has a lower exploratory capacity than other species, such as salmonids.

Thus, for example, at Conowingo the remote attraction was determined at 90% in 2010 and 64% in 2012, respectively. The difference can likely be explained by peak flows during the month of May which were clearly higher in 2012 (1,474 m^3/s) than in 2010 (924 m^3/s).

At York Haven, the study carried out in 2010 revealed that 82% of shad came near the fishway entrance. The dam is not very wide and the flow in the fishway is high compared to the other concurrent flows. The development is located on the arm of the river and is supplied by a flow of 56 m^3/s under regular hydrologic conditions. The fishway entrance is supplied by a flow of 7.5 m^3/s (≈ 13%).

At Vernon, in 2011, only 58% of fish appeared near the fishway entrance. It has to do with the peak flows during the month of May that year, but also with operational problems with the gate located at the downstream fish entrance, which did not ensure the attractiveness of the falls (J. Ragonese, pers. comm. 2015).

At Lowell, Sprankle (2005) highlighted that only 50% of fish reach the vicinity of the fishway entrance.

The second difficulty for fish is to enter the fishways. Having fish come close to the entrance is not enough; they must be able to detect the presence of the fishway and that conditions be favourable in order for them to enter inside.

There is no site where all the fish that came near the fishway entrances actually entered them. The **close attraction** ranges from 31 to 81% (with the exception of the Tuilières site on the Dordogne where the zero value observed does not reflect reality).

At Conowingo, 69% (2012) to 81% (2010) of shad appearing near the entrances entered the fishway. These close attraction percentages are amongst the best out of all the sites monitored.

At Vernon, a 42% close attraction was observed during the 2011 telemetric study.

At York Haven, only 32% of the fish who approached fishway entrance also entered. It is alleged that the release of the attraction flow without prior dissipation near the fishway would create a highly oxygenated area not particularly conducive to the surveying of shad.

Monitoring was also conducted at the navigation locks. At Lock and Dam No. 1, on the Cap Fear River, 55 to 83% of the fish present downstream of the obstacle entered the lock. The fishway operates three times a day (7AM, 12PM and 5PM) and harnesses a consistent flow, ranging from 24 and 32 m^3/s, compared to the watercourse flow (an average of 130 m^3/s in April and 67 m^3/s in May at the Lilington Station). At Pinopolis, on the Cooper River, 79% of fish downstream of the lock enter it.

In the end, the **overall attraction**, which is made up of the remote and close attractions, varies depending on the site, from 15-20% to approximately 70%. The median is 53% (1st quartile: 33.5%; 3rd quartile: 73.5%), independent of the development and the type of fishway.

Such results can be associated with the fairly limited exploratory ability of the shad (see Section 2.2), which is lower than for other species, such as salmonids, and also the locations of the fishways, their attractiveness, and sometimes the fact that there are too few of them.

4.4.1.1 INSUFFICIENT NUMBER OF FISHWAYS

The installation of fishways at the end of each attraction lane is required to achieve proper remote attraction.

At several sites along the U.S. East Coast, a fishway was installed at the plant and another at the dam, given the moderate design flow compared to the watercourses' hydrology and the presence of bypassed sections. At Holtwood, the plant design flow corresponds to approximately 130% of the average watercourse flow in May. However, there are no available data on the number of shad using these fishways (R. Moyer, pers. com. 2015). At Lowell, the plant design flow represents approximately 150% of the average watercourse flow in May. The number of fish using the fish ladder is unknown. At Holyoke, the distribution of shad passages between the two fishways seems equivalent (USFWS, 2015 ; R.F. Murray Jr, pers. com. 2015), the flow diverted by the plant representing 60% on average of the watercourse flow in May. At Turners Falls, almost 15% of fish use the dam fishway, located on the upstream section of the bypassed section, when it is supplied by a flow corresponding to approximately 15% of the watercourse average flow in May and the maximum diverted flow by the Gate House is close to the hydrology in this same month. These examples and results illustrate the appeal of installing fishways on the various waterways (tailrace and bypassed section) as soon as they are likely to be attractive.

Only one fishway was installed at the plant of the Safe Harbor development, on the Susquehanna, given its very high design flow (about 250% of the yearly average watercourse flow in May) even with it bypassing a section of river.

At York Haven, only one fishway was installed on an arm of the Susquehanna, supplied by a minimum flow of 56 m^3/s, i.e., 5% and 7% of the respective average flows in the watercourse in May and June. Depending on the year, between 27% and 67% (average of 44%) of fish come to the weir located on the arm. However, between 62 and 100% (average of 83%) of shad arrive at the foot of the plant, whose design flow represents 42 and 59% of the average May and June flows (York Haven Hydroelectric Power, 2011). The installation of a second fishway at the main weir located in the extension of the plant is planned as part of the authorisation renewal (C. Freese, pers. com. 2015).

At the Conowingo site, the two structures installed at the plant, which are very wide, show the advantage of installing multiple devices. The lift installed on the right bank (West lift) is only used to capture fish for artificial reproduction as part of the species restoration plan (no opportunity for direct transport of fish upstream), while the one on the left bank (East lift) is the main upstream migration device on site. These two lifts are supplied by similar flows. From 1991 to 2011, shad that used the West lift represent 17% of the controlled numbers in the two lifts, although it was in operation nearly half the time than the East lift (Susquehanna River Anadromous Fish Restoration Cooperative, 2012).

In France, for the shad but also other migratory fish, the installation of one fishway at the hydroelectric plant and one at the dam is becoming more common (Sordes on the Gave d'Oloron, Puyoo on the Gave de Pau, Golfech (project) and Le Ramier on the Garonne, Mauzac on the Dordogne, Langeac on the Allier, etc.)

Achieving proper remote attraction can also require the installation of several entrances.

Several entrances connected by a horizontal gallery to only one fishway were installed at several sites on the East Coast (Holyoke plant, Gate House at Turners Falls, Conowingo East lift, Holtwood plant, Safe Harbor). The percentage of passages in the various entrances was only assessed at Gate House where two entrances located on each bank were linked to the fish ladder. The majority of fish incursions into fishways (189 out of 244, 77%) and upstream migration (76 out of 112, which is 68%) are through the entrance on the right bank, which was recently modified, while 23% of entrances and 32% of upstream migrations are observed through the former entrance, where hydraulic conditions are not optimal (Castro-Santos and Haro, 2014).

In France, some structures are equipped with several fishways (Vichy on the Allier, Haitze on the Nive, etc.) or entrances (Mauzac on the Dordogne, Châtellerault on the Vienne, Carbonne on the Garonne, Iffezheim, Gambsheim and Strasbourg on the Rhine, Sauveterre on the Rhône, etc.). At Gambsheim, where there are two entrances located over the turbines draft tubes and one entrance is brought forward 60 metres downstream on the riverbank, the RFID surveys show that 93% of migrating salmon and 76.6% of cyprinids (barbel, bream and common nase) use the entrances located over the draft tubes (Travade & *al.*, 2013 ; Tétard & *al.* 2014).

4.4.1.2 BADLY POSITIONED AND UNATTRATIVE ENTRANCES

LOCATION OF ENTRANCES AND DOWNSTREAM HYDRAULIC CONDITIONS

The entrances must absolutely be positioned in calm areas, where fish will move in greater numbers, on the most upstream segments of the obstacles. Turbulent and oxygenated areas, where shad rarely stay, must be avoided (MRTC, 2010; ALDEN, 2011; Normandeau and Gomez and Sullivan, 2011).

At numerous sites, the areas highly disturbed from an hydraulic point of view (updraft, etc.), especially at the exit of hydroelectric station turbines, do not offer good attraction capabilities at the entrances. That is why several entrances (from 2 to 5) were originally linked to fishways via collector galleries at the Holyoke power plant, Cabot power plant, Vernon, Lawrence and Lowell sites. The majority of them have since been closed because fish could not detect their presence due to their location over the turbine exit.

At the Cabot hydroelectric station and at Vernon, only one entrance on the bank was maintained where the entire flow was concentrated.

At Holyoke, the entrance located in the middle of the tailrace was closed and only the two other entrances located on each bank are now supplied.

At Lowell and Lawrence, the entrances that are furthest from the lift are no longer supplied and only the entrance on the bank, closer to the lift, is operational. Apart from wanting to concentrate the flows in fewer fishways, this choice was also dictated by numerous observations of many fish entering the tunnel using the furthest entrance and coming out through the other entrance, where they have to negotiate a 90-degree turn to face the fish trap.

In some cases, the prioritisation of the units' operation at several hydroelectric plants, when inflows are lower than the plant turbine capacity, was established. The objective is to allow fish to come near the fishways entrances while ensuring satisfactory attraction.

At Vernon, the unit which is the closest to the entrance is started first (J. Ragonese, pers. com. 2015). At Holtwood, the old plant, located near the lift, has priority up to a flow of about 255 m^3/s. The outlet of unit 1 was extended in order to exit into the bypassed section and prevent turbulence in the fishway entrances. Units 3, 5 and 6, located on the same bank as the lift but not directly next to it, are started first (R. Moyer, pers. com. 2015). Unit 2, nearest to the lift, is started last. These rules were established empirically. They are still being applied even it is impossible to assess their actual effectiveness using information from the various studies. At Safe Harbor, the two units located near the lift are shut down first (R. Wagner, pers. com. 2015).

At certain sites (Conowingo, Holtwood, Safe Harbor), the choice was made to locate several entrances at different distances from the structures to ensure attractive fishways under different operational conditions for the power plants in areas likely to be frequented by fish. At Conowingo, the two entrances are alternately supplied depending on the plant operations. Fish avoid highly turbulent oxygenated areas downstream of the Kaplan turbines when in operation (Normandeau and Gomez and Sullivan, 2011). Since the upstream entrance is influenced by the operation of the units, it is not supplied when they are not in operation. Otherwise, it is the downstream entrance, located more than 80 m from the plant, which is operational (Figure 4-3 and Figure 4-4).

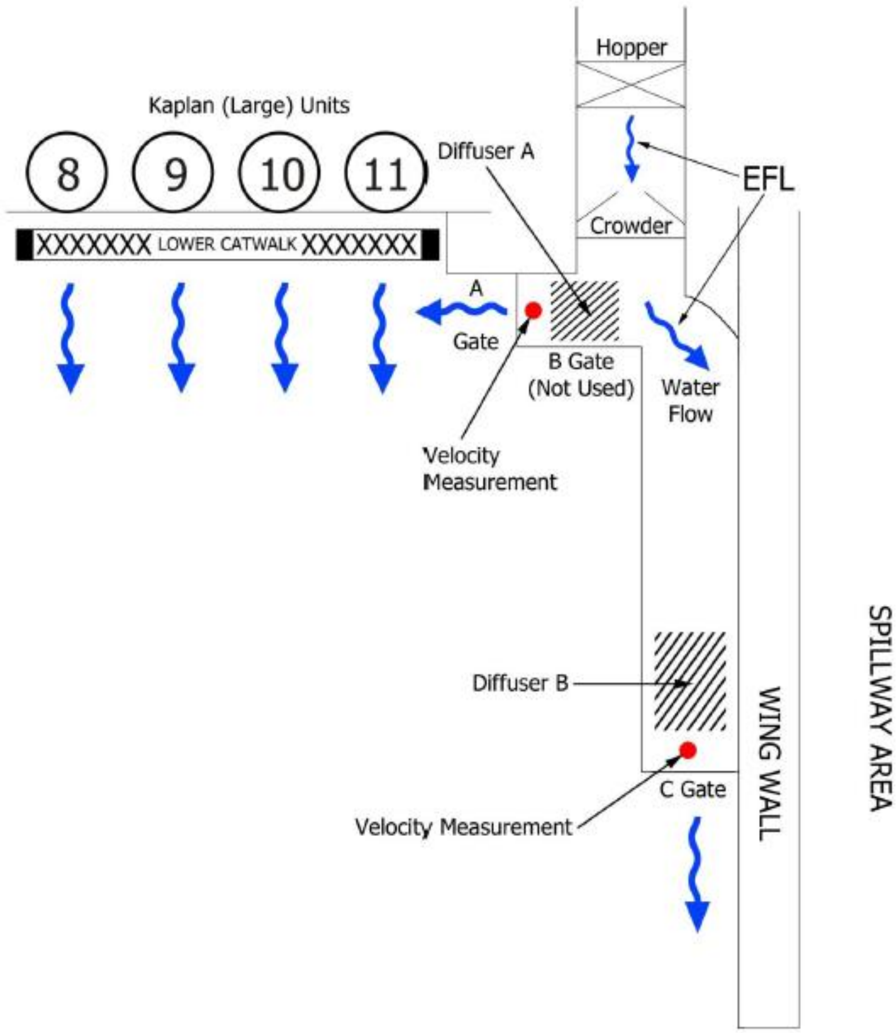

Figure 4-3 **Summary Plan of the Two Entrances of the Conowingo Lift on the Susquehanna River (Normandeau and Gomez and Sullivan 2012).**

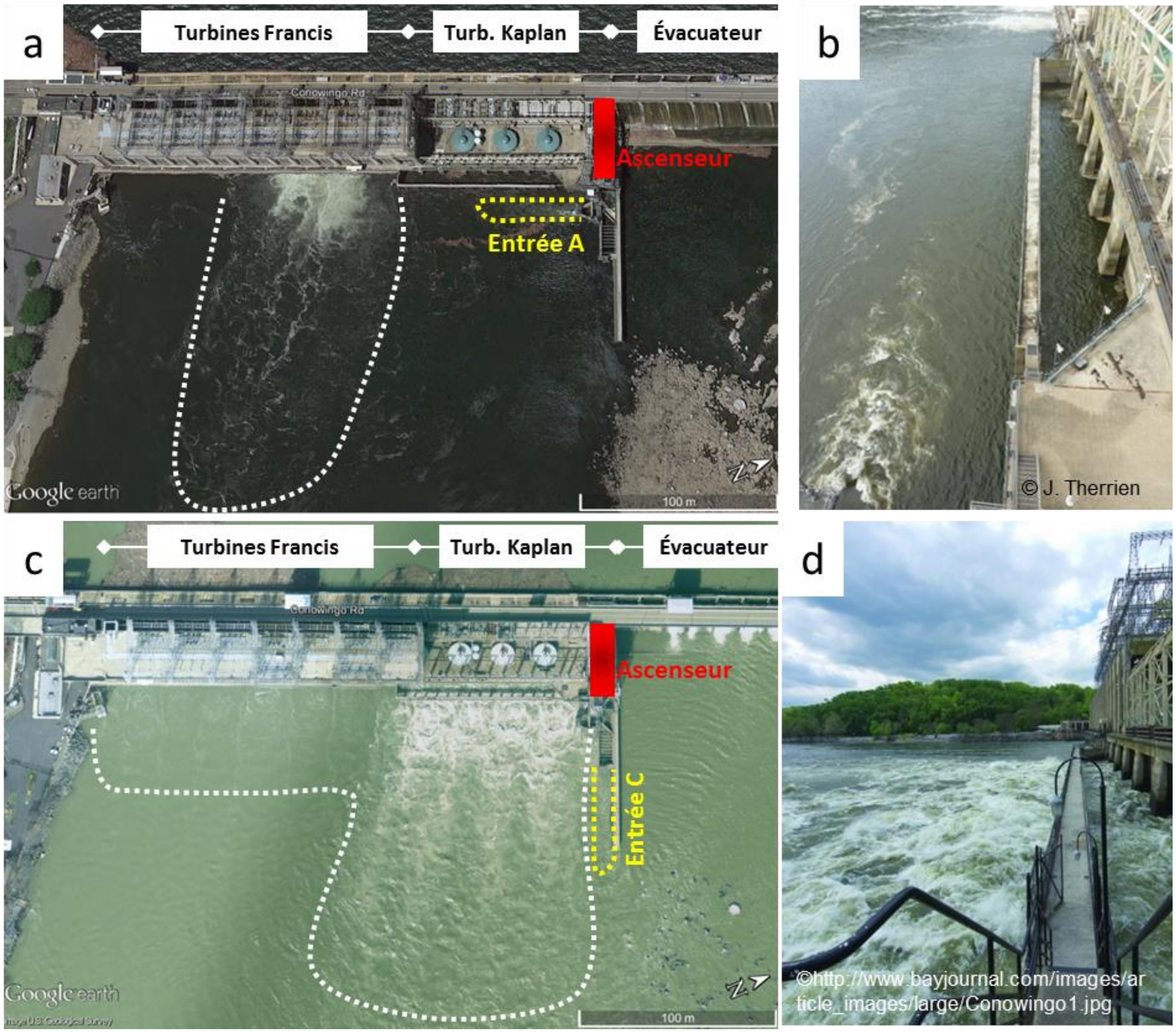

Figure 4-4 **Impact of Units Operation on Hydraulic Conditions Downstream of the Conowingo Station on the Susquehanna River a) Francis turbines in operation and supply at entrance A b) stream at the exit of entrance A c) Kaplan turbine in operation and supply at entrance C d) Hydraulic conditions at the exit of the Kaplan.**

Finally, at other sites, the location of the entrances was modified after monitoring. At Gate House, the entrance located on the right bank was moved downstream to a less turbulent area from a hydraulic point of view (upwelling, velocities, substantial aeration, etc.) and that is more frequented (Figure 4-5) by shad (Castro-Santos *& al*., 2014). Moreover, its supply flow was increased by reducing the flow of the left bank entrance. The passage of the structure was significantly improved, even though it is still low, as demonstrated by the telemetry monitoring and the evolution of the Cabot – Gate House transfer rates determined by counting (average of 3.6% for the 1983-2009 period; 9.4% for the 2010-2015 period).

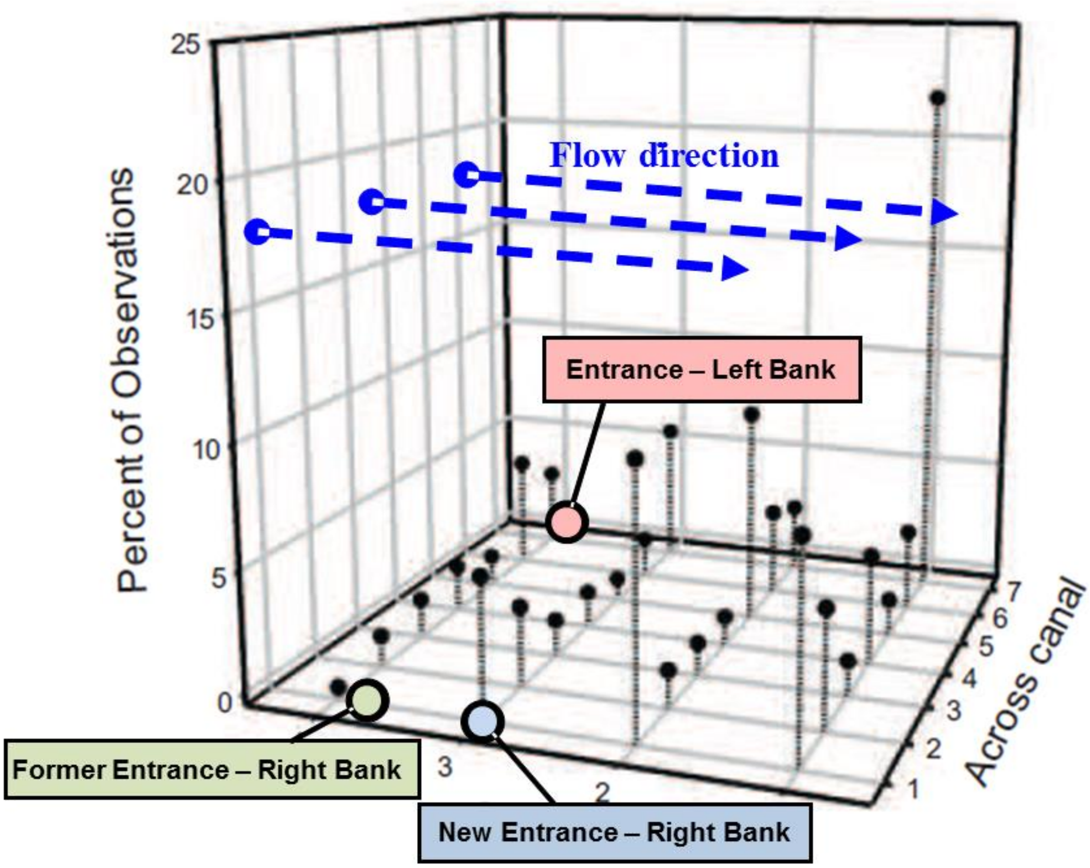

Figure 4-5 **Telemetry Monitoring of Shad Movement Downstream of the Gate House Structure (Turners Falls Site, Connecticut River) and Location of the Fishway Entrances (Castro-Santos & Haro, 2014).**

At Lowell, the entrance was recently moved downstream of the highly turbulent area by installing a 1.2 m deep lateral deflector guiding the flows.

Sometimes, the entrances are perpendicular to the main flows which shear the streams and greatly reduce their attraction. This is what happens at Safe Harbor: the entrance, located directly downstream of the unit exit, was condemned.

The corners or the recirculation areas often represent areas highly visited by shad (Larinier & al., 1994). This was particularly observed on the Holtwood site, in a hydraulically protected area located upstream of the units exit and of the two lift's entrances (Tryninewski & al,. 2012), and more recently on the Bergerac site where many fish stay in a calm area located between the turbine exit (highly turbulent area) and the fishway (whose entrance is located some ten metres downstream). Two broad solutions are possible: the implementation of an entrance in these specific areas or reducing their surface. The latter option was chosen at Holtwood in 2013.

Finally at other sites, such as the Holyoke and Turners Falls dams, the overflow of controlled flow conceals the lifts entrances. Reflections are used to address the issues of fishway entrance attraction by extending it downstream (Turners Falls) or by redirecting the flows (Holyoke).

HYDRAULIC CONDITIONS NEAR THE ENTRANCES

Beyond the hydraulic conditions directly downstream of the fishways, which seem to be essential to ensure satisfactory attraction at the entrances, several parameters are likely to have an impact on the capacity of the fish to detect the fishways and to enter them.

With regard to **supply flow**, the criteria used in the United Stated and in Europe are fairly comparable.

On the U.S. East Coast, flows harnessed to ensure the fishway attraction vary from 2.3 to 17 m^3/s, with inlet flows ranging from about 2.3 to 10 m^3/s. They represent 0.7 to 2.5% (average of 1.5%) of the annual average flow of watercourses (8% at Turners Falls where three fishways are installed) and 0.5 to 2% (average of 1.1%) of the average flow of watercourses (6.2% at Turners Falls and 5% in the channel of York Haven) during the main shad migration period. For the hydroelectric plants, the flows harnessed in the fishways represent 0.35 to 2.9% (average of 1.4%) of the maximum turbinated flows and 0.6 to 2.9% (average of 1.6%) of the average turbinated flows in May. The highest percentages are observed at Holyoke and at the Cabot station.

In Europe, especially in France (see Table 3-2) fishways harness flows ranging from 1-1.5 to 6.5 m^3/s, and which can reach 15 m^3/s on the largest structures such as on the Rhine. These flows overall represent 1 to 4% (average of about 2%) of the yearly watercourse average flows. In May, during when significant migration occur at all sites, fishway supply represents 0.8 to 4% (average of about 1.9%) of the watercourse average flow. For the hydroelectric plants, flows harnessed in the fishways generally represent 0.9 to 3.5% (average of 1.7%) of the maximum turbinated flows. In Portugal, the fish ladder installed at the Açude-Ponte dam on the Mondego River is supplied by a flow of about 2-2.5 m^3/s (Almeida, pers. com., 2015) which corresponds to almost 5% of the concurrent flows in May in 2013 and 2014, and almost 20% of the flow in 2015 (year with a very low flow coefficient)

It appears difficult to establish a relationship between a fishway's supply flow, its attraction and its overall efficiency. Monitoring is limited and many factors can impact the attraction of the fishways. However, at several sites, **inadequate flows** are often implemented to ensure suitable fishway attraction (for example, see Sprankle, 2005 on the Lowell site on the Merrimack; or FERC, 2014 on the Conowingo site on the Susquehanna). Thus, at Conowingo, as part of the authorisation renewal, it was requested to increase the East lift attraction by mobilising a flow of about 25 m^3/s which corresponds to the flow that was initially planned (FERC, 2014).

At several sites, the decision was made to condemn certain entrances which seemed unattractive in order to both concentrate flows in a reduced number of fishways and to reduce the flows allocated to non-turbined devices (Holyoke, Cabot plant, and Vernon on the Connecticut; Lawrence and Lowell on the Merrimack). On the Gate House site, the supply flow at the entrance most used by fish was increased in recent years, but the second entrance located on the opposite bank was not altered.

Falls at the entrances, which control the flow velocities, are likely to greatly impact fishway attraction. At American sites for which reliable information is available, falls at the entrances are maintained between 0.15 and 0.25 m. In France, values are generally between 0.20 and 0.25 m. This corresponds to average velocities between 1.7 and 2.2 m/s. For example, the small proportion (42%) of fish present downstream of the fishways that entered the fish ladder observed by telemetry at Vernon in 2011, seem to be linked to a poor management of the gate located near the fish entrance, which did not ensure an attractive downstream fall (J. Ragonese, pers. comm. 2015). These results are confirmed by the low transfer rate observed by video count that year (0.3%) compared to Turner Falls. Changes were made the following year, allowing the transfer rates to return to rates similar to those observed in the 1990s (from 60 to 70%).

DIMENSIONS OF ENTRANCES

The **dimensions (width and depth) of entrances** are likely to greatly impact the entry of shad inside fishways, in particular due to their schooling behaviour. At American sites for which data are available, widths vary from 1.2 m (Lowell) to 3 m (Holtwood) and depths from 1.2 m (Lowell) to 2.4 m (Holtwood). It does not seem possible to establish a direct link between the entrance dimensions and their attraction. However, NWFS (2000) notes that on the Columbia River, salmon prefer the largest and deepest entrances, if they are situated on banks. The smaller entrances are less used, with a significant number of fish coming back out.

4.4.2 PROGRESSION INSIDE THE FISHWAYS

Passage through the upstream migration fishways, meaning the capacity of the fish, once entered, to reach the upstream of the obstacle, varies most often between 20-30% and 70%.

For lifts, it is often greater than 50% and reaches a maximum of about 70%.

For fish ladders, it varies considerably depending on the type and characteristics of fishways. Lower values are observed in Ice Harbor fishways, originally designed for salmon. However, more than 80% of fish overcome the vertical slot fishway at Gate House.

The lack of efficiency is linked to the fact that shad enter fishways, using many entrances but exit without reaching the other side. Such behaviour is also observed in other species, such as the Atlantic salmon (Larinier & *al*., 2005 ; Karlsson, 2013) or the Pacific salmon (Reese, 2012 ; Clabough & *al.*, 2013).

At Conowingo, for the two years of monitoring, 30% of fish entered the fishway several times before reaching upstream. On average, fish make 1.7 incursions (62 incursions for 37 fish).

At Lowell, the 2011 monitoring highlighted that the 2 fish that overcame the structure entered the fishway 3 times and 20 times. A fish entered three times in the downstream section of the fishway without passing through the entire structure.

In 1993 at Lawrence, fish entered the fishway 33 times on average.

At Bergerac, the shad that overcame the obstacle entered the fishway twice. At Golfech, a shad entered the fishway 10 times without reaching the other side. The fact that fish must pass through a 90° corner immediately upstream of the entrance in order to enter the holding tank of the lift could explain such behaviour.

Fish can face four broad types of difficulties:

- → in the downstream sections of the fishways, related notably to likely behavioural reluctance when transitioning between the watercourse and the fishway, problems in moving forward through the collector tunnels and traveling through the other zones of the attraction flows;
- → further upstream, linked to internal hydraulic conditions and to the fishway length;
- → at various levels of the fishways, related to the presence of steep turns;
- → difficulties when facing lifts where fish have to enter and then stay in the holding tank.

4.4.2.1 ISSUES IN THE DOWNSTREAM SECTION OF FISHWAYS

Shad exiting the fishways illustrate their reluctance of fish to pass from an open environment, the watercourse, to a closed and confined one, sometimes noisy and poorly lit, and most of the time, highly artificial (civil engineering). This reluctance is likely reinforced by the fish's schooling behaviour.

In many cases, the flows harnessed to ensure the crossing of shad are consistent and require the addition of an additional flow in the downstream section of the fishways which can disorient fish and disrupt their upstream migration. At most of the sites visited in the United States, supply flows are injected through horizontal gates located at the bottom of fishways.

At Conowingo, significant fish accumulation immediately downstream of the attraction flow injecting screen observed in situ indicates the difficulties faced by shad, all the more as they must negotiate a 90-degree turn at the injection point to enter the holding tank of the fish ladder.

At York Haven, even if no information proves it, it is likely that the downstream part of the fishway where the attraction flow is injected represents a problematic area for fish, given the significant ascent phenomena.

At Lawrence, problems were noticed immediately downstream of the non-return device of the lift's holding tank. Modification to the attraction flow injection floor so as to notably reduce aeration significantly improved the situation. The internal efficiency of the fishway (% of shad entering the fishway and exiting upstream) went from 10% to more than 70% (Lawrence Hydroelectric Associates, 2013).

The collector galleries have been condemned at most of the sites visited on the East Coast. This is explained by the little attraction of entrances located over the turbines' tailrace as well as by the exit of fish by intermediary entrances, specifically the case at the Lowell and Lawrence fishways on the Merrimack. Similar observations were made for the salmon, especially on the Columbia River (Reese, 2012). In France, at the Golfech site, no monitored shad was able to negotiate the 90-degree turn at the connection between the two fishway's entrances (Verdeyroux & al., 2015).

4.4.2.2 ISSUES REGARDING HYDRAULIC CONDITIONS INSIDE THE FISHWAYS

Internal flow conditions must be perfectly adapted to the swimming capacity and behaviour of the species, especially since the distances to be covered are significant. Such unfavourable conditions could cause significant transit times and/or the descent of entire schools of fish (fall back activity) which is likely to greatly reduce the efficiency of the fishways.

Results are generally bad for Ice Harbor-type fish ladders, such as the ones at Turner Falls, which were originally designed for salmon and are characterised by streams plunging into the basins, even when the fish ladders have been modified (sealing of one of the slots). This can be explained by the type of streams (which are not exactly streaming), and the degree of aeration and agitation in the ladders (dissipated power in ladders, about 200 W/m^3).

Thus, on average, 20% of fish that enter the Cabot hydroelectric station fishway (length of 263 m; 66 ladders; fall between ladders: 0.3 m) reach the upstream. At Turners Falls (length of 180 m; 35 ladders; fall between ladders of 0.3 m), 15% of fish reach the upstream. Median time for passage through these two fishways varies depending on the year; from 5.6h to more than 24h at the Cabot hydroelectric plant, and from 4.5h to 6.9h for the spillway. Average parking time per basin ranges from 5.7 to 22 min. This means that fish that enter the fishway in the afternoon have little chance of reaching the upstream. Many of them descent the fishway at the end of the day when daylight fades (Haro and Kynard, 1997; Sullivan & *al*., 2002).

Five weirs were modified in the downstream section of the fishway at the Cabot hydroelectric station in order to approach surface streams. The number of shad that crossed the fishway, as well as the time spent in the ladders, was compared to what was observed in a section of the fishway directly upstream and of the same dimensions, but where falls were not modified (Haro & *al.*, 2001; Sullivan, 2004). The comparison made by Sullivan (2004) in 2000 reveals a passage rate in the first four modified weirs of 91.06% vs. 79.37% in the unmodified section. Furthermore, fish stayed in the fishway for significantly less time (median of 4.85 min in the modified section vs. 23.43 min in the unmodified section).

At Vernon, thanks to the reduced number of Ice Harbor-type ladders (25 ladders in the downstream section, and then 24 baffle ladders) and the changes made before the 2012 migration season helped improve the passability in recent years, judging by the transfer rates at Gate House.

Concerning tested slot fishways, low efficiency observed at York Haven and Gate House must be carefully assessed.

At York Haven, as stated in the previous section, it is very likely that the problems faced by fish are in the downstream section of the fishway, at the attraction flow injection.

At Gate House (Turners Falls development), as clearly demonstrated by the RFID studies (see Table 4-5), problems occur in the collector gallery (connected to the two entrances of the Gate House and to the fishway located near the spillway) which leads the shad to the slot fish ladder. The average efficiency of this fish ladder (length of 70 m; 8 ladders; falls between the ladders: from 0.07 to 0.3 m) is 85%. The maximum parking time per ladder is at most a few tens of seconds on average, which is clearly shorter. Similar results were observed for the European shad at the Mauzac vertical slot fish ladder (length of about 80 m; 22 fish ladders; falls of: 0.3 m) on the Dordogne.

4.4.2.3 ISSUES NEGOTIATING TURNS

Fish generally have serious difficulties negotiating turns within fishways, as revealed by Haro & *al.* (2001) or Sullivan (2004) at the Cabot hydroelectric station and the Turners Falls development. Sullivan (2004) also indicates that parking time in the turning basins is clearly more significant and that transfer rates are the lowest observed in the fishway. It is even more difficult when there are 180-degree turns. Thus, for 2001 and 2002, parking time of shad in the 2 ladders with 180-degree turns were on average over 44 minutes, with maximums exceeding 11 hours. In straight ladders, fish only stay a maximum of a few seconds or minutes.

At Conowingo, *in situ* observations seem to indicate that shad have a hard time negotiating a 90-degree turn at the attraction flow injection point in order to enter the lift's holding tank located directly upstream.

Major problems were also observed in the collector galleries connected to several entrances (Lawrence and Lowell on the Merrimack, Gate House on the Connecticut, Golfech on the Garonne). In all cases, fish, who must negotiate a 90-degree turn at the junction with the entrance located in the upstream section of the gallery, often exit the fishway by that entrance. It was decided to only maintain the upstream entrance at the Lawrence and Lowell sites.

4.4.2.4 DIFFICULTIES ENTERING AND STAYING INSIDE THE LIFT'S HOLDING SYSTEMS

Fish have problems entering and staying long enough in the lift's holding systems.

At Conowingo, in 2010, 63 of the 65 fish that entered the lift were seen downstream of the non-return device (crowder), but in the end, only 40 reached the upstream (61%). In 2012, more accurate data show that out of the 29 fish that entered the fishway, 26 proceeded upstream of the crowder (90%), but only 17 were captured and reached the upstream, which represents 59% of the fish that entered the fishway and 65% of those who passed through the crowder. It does not seem like the fish show reluctance at crossing the crowder; however, a significant percentage (35%) of fish were able to exit the holding tank.

In terms of ladder upstream migration frequency, rhythms, normally varying between 10 min and 1 hour during the main migration period, are fairly similar between sites. The decrease of the Conowingo lift upstream migration frequency in 2012 compared to 2010 (1h in 2010 and 30 min in 2012) did not apparently improve the passability. This result could be explained by the hydrology that was clearly less favourable in 2012. It is moreover requested as part of the dam authorisation renewal that an upstream migration frequency of 15 min be maintained (FERC, 2014).

The configuration of the crowder is however slightly different, although it seems impossible to determine which configuration is more appropriate. Distances between doors vary from about 0.3 m at Conowingo and Holtwood to 0.6 m at Lowell, and about 1 m at Safe Harbor.

At Lawrence, the crowder was modified: the initial V system was transformed into a baffle by closing one of the doors. This modification could explain the clear improvement between monitoring conducted in 1993 compared to 1994-1995. However, the attraction flow injection was optimised around the same time, and we cannot distinguish the effects of the two modifications.

At Lowell, the initial distance of 1.2 m was modified to 0.6 m, although it was impossible to actually estimate the efficiency.

Finally, it is interesting to talk about the tests carried out at the Locks and Dams 1 on Cap Fear River. The best results obtained in 1998 by Moser & al. (2000) have to be linked with the closing of one of the two downstream doors in order to notably increase the fishway's attraction. It is also possible that this improved fish retention.

4.5 CONCLUSION

It appears that the fishways studied possess a limited efficiency for shads. As previously stated by Larinier and Travade (2002), an efficiency of 75% is exceptional, 50% is excellent, and 10-20% is unfortunately far too common. A global efficiency lower or equal to 50% was observed in the vast majority of sites visited in the United States in 2015 (median: 26%; 1st quartile: 13%; 3rd quartile: 48%) (see Table 4-4). The best results, in the range of 70%, were observed at structures (Holyoke, Safe Harbor, Vernon in recent years, Pinopolis Lock, and Locks and Dams 1) very different in terms of size, supplied flows, types of fishways, etc. Many explanations can be provided to understand these results: for Holyoke, the presence of two fishways, one at the plant and the other at the dam, as well as the supply flow of the plant's lift which represents nearly 3% of the maximum turbinated flow; at Safe Harbor and Vernon, the fishway's attraction, depending on the location of the entrances and the hydroelectric station's turbines operation directives; at the Pinopolis Locks and Locks and Dams 1, the importance of mobilised flows.

Shad, like all other fish, face three main problems at the obstacles: being near the fishways, finding the fishway entrances and entering and progressing inside to reach the upstream side.

Experience feedback analysed as part of this work would suggest that, based on the criteria selected up to now, it will be hard to obtain efficiencies higher than 70-75%, which corresponds to an overall efficiency of about 90% for each of the three stages.

In this context, cumulated impacts caused by various structures constructed on a same migratory axis will rapidly become significant and make the management and restoration of populations hard, especially when structures are located in low sections of the catchments, downstream of the best areas for reproduction and growth of juveniles.

Note that the vast majority of sites investigated for shad and presented in this document are located on significant watercourses (mean annual discharge of several hundred m^3/s), meaning that achieving good fishway attraction is not easy.

However, it seems possible, even for this type of fishway, to further improve the efficiency of passage systems by being more ambitious when it comes to certain sizing criteria. Special attention must be paid to the following elements:

→ in view of the migratory behaviour of shad and of the difficulties faced by fish when entering the fishways, the size of fishways and entrances must be significant so as to prevent the splitting up of schools;

→ fish must be able to come quickly and often to the entrances and inside the fishways. The migration windows are indeed very narrow and once at the base of the obstacles, the urgency of fish to overcome the structures seems limited, at the very least more limited than other species such as salmonid. Further, numerous shad, as is the case for salmonid, "need" to come near the entrances or enter the fishways several times before actually passing through them. The location of fishways, their number, attraction (supply flow vs. concurrent flows), hydraulic conditions at the entrances (in relation to the hydroelectric plant operation) and internal hydraulic conditions are all factors that need to be taken into consideration.

The fishways must be operational and attractive for watercourse flows generally corresponding up to about twice the annual mean discharge. In this context, the concurrent flows are significant and because of them, the fishways must be supplied with significant flows. The location and orientation of the entrances are also important factors to ensure sufficient attraction in relation to hydraulic conditions downstream of obstacles (high-velocity or overoxygated areas, ascent, etc.).

5 RECOMMENDATIONS FOR THE DESIGN OF FISHWAYS

The recommendations provided hereinafter are meant, a minima, to generalise the best efficiency obtained up until now (about 70%), and if possible be able to obtain higher efficiencies. These recommendations are based specifically on Larinier and Travade (2002); NOAA (2012); Towler & *al.* (2013); and Orvis & *al*. (2016), but also on information that was acquired thanks to both the document review as part of the present work and the site visits and exchanges conducted in the spring of 2015 on the U.S. East Coast.

5.1 HYDROLOGY AND OPERATIONAL RANGE OF FISHWAYS

Since the shad migration period is short, normally 30 to 50 days, it is important to make sure fishways are in fully satisfactory operation during most of the time and for the majority of flow conditions occurring during this period.

In general, the knowledge gained on the various watercourses studied in the United States and in France brings us to recommend designing fishways for flow values of around twice the mean annual discharge of the watercourse.

In greater detail, based on the analysis of flow frequency during the migration period, a mode of operation of the fishways that is satisfactory 80% of the time between Q_{10} and Q_{90} (flow values not exceeded 10% and 90% of the time) as recommended by DVWK (2002), or 90% of the time between Q_5 and Q_{95} as recommended by Orvis & *al.* (2016) would be sought. The increase to 90% is warranted for shad given its short migration period. This is consistent with Larinier & *al.* (1994) which indicates that it is essential for a shad fishway to be operational during the entire migration period.

On watercourses colonised by shad, the presence of other migratory (salmon, sea trout, lamprey, eel) or holobiotic species will entail taking into account other migratory periods, and thus other flow ranges that will need to be accommodated.

The flow frequency during the migration period should be analysed over several years, 10 to 20 years if possible, including a variety of situations. In the absence of hydrologic data near the site, information will be extrapolated from relevant available data.

5.2 NUMBER OF FISHWAYS FOR A DAM BYPASSING A WATERCOURSE SECTION

When it comes to a dam bypassing a watercourse section, the main concern is to define where it is necessary to install a fishway: bypassed section and/or plant. This decision must be based on:

- distribution of flows between the bypassed section and the plant;
- flow organisation and velocities at the confluence of the various migration routes;
- length of the tailrace and bypassed sections;
- observations on the presence/absence of shad.

Sometimes, differences in water temperatures between the migration routes (especially the tailraces and bypassed sections) can impact the fish's behaviour.

In order to reach the best efficiency for shad, a fishway must be installed in the various fish accumulation areas.

It appears that, in certain configurations, even limited flow values are likely to attract a significant proportion of fish .This is why two fishways were installed at the majority of dams visited in the United States that bypassed a section of watercourse, one at the plant and another at the spillway (see Section 4.4.1.1). **We recommend considering the installation of multiple fishways, at the plant and at the dam, when the bypassed sections and the plants are supplied by significant flows during the shad migration period.** Only when hydroelectric developments are heavily equipped, compared to the flows during the migration period, is installing only one fishway at the plant possibly sufficient (e.g. Safe Harbor with a design flow of more than 250% of the average flow of the watercourse in May).

Since the shad's migration period is short, it is also possible to concentrate the flows in the sections with fishways. For example, the turbinated flow of a plant without a fishway can be limited so as to reduce its attraction and increase the bypassed section's attraction at the end of which a fishway can be found. However, production loss can be significant.

5.3 NUMBER AND LOCATIONS OF FISHWAYS NEAR THE OBSTACLES

In general, **fishway entrances must be located in the vicinity of the most upstream fish accumulation areas,** where fish are stopped by an impassable fall, or by currents or turbulence that are too strong. Entrances shall **preferably be located near banks**, which correspond to the main fish accumulation areas (Larinier & Travade, 2002; ALDEN, 2011; Williams & *al.*, 2012; Castro-Santos & *al.,* 2014). When several fishways must be developed, it is important in the vast majority of cases to first make sure they are located along each bank.

In all cases, fishways must be located in **undisturbed or little-disturbed areas from a hydraulic point of view**. Placing entrances over draft tubes, in calm areas, is an interesting scenario, insofar as the water depths are significant enough (these areas are often non-existent or too shallow) (see the Safe Harbor case on the Susquehanna, as well as monitoring performed on salmonid and cyprinid at the Gambsheim fishway on the Rhin- Travade & al., 2013; Tetard & al., 2014). Conversely, entrances located directly downstream of the draft tubes where flows are very disturbed must be avoided.

At an obstacle (hydroelectric plant, weir), an entrance should be placed in each shad accumulation area. The number and location of entrances depends on the configuration of the structure (width, orientation compared to flows), the flow management, downstream watercourse topography, etc. Further, these areas can vary depending on the hydrological conditions and the plant operation. Observing the behaviour of shad downstream helps guide the choices made. If such observation is impossible, one can proceed by analogy with similar existing sites or base the selection on scale models or numerical modelling studies. Larinier & Travade (2002) is the main reference for installation principles depending on the configuration of the obstacle.

Monitoring conducted on certain sites revealed that several entrances or fishways may be necessary so as to improve the passability (see Section 4.4.1.1), especially when the obstacles are wide and that their configuration does not allow for the concentration of fish in a specific area (no guidance). However, increasing the number of fishways does not always mean an increase in efficiency. Several fishways located on the U.S. East Coast were originally designed with numerous entrances (collector galleries), but the majority of sites only kept one or two entrances where flows were concentrated. Entrances that were condemned are mainly located directly over turbine exits where the attraction is highly reduced because of upwelling and turbulence.

We recommend considering the installation of several fishways for shad when the width of the obstacle is greater than 20 m, as recommended by Larinier & Travade (2002). **When the obstacle's width is greater than 100 m, it is necessary, in the majority of cases, to install several entrances** connected to one or numerous fishways, as recommended in a general way by Schmutz & *al.* (2015). With the exception of very big structures installed on very large watercourses, it would appear that the installation of 1 to 4 properly located and designed entrances allows for good efficiency. Properly orienting the obstacle with regard to the flows, or guaranteeing the restoration of the majority of flow in the targeted hydrologic range in a specific area, can help limit the number of fishways needing to be installed.

At a hydroelectric plant, flow passing through downstream migration systems, generally non-dissipated and likely to attract fish downstream, must be discharged near the upstream migration fishway entrances without impeding the attraction. If these flows are attractive, they shall be discharged far downstream or the location of the entrances shall be adjusted.

The number of fishways to be built, at a given obstacle, depends on the number of entrances, their location and the possibility of connecting the entrances to each other. Obviously, installing entrances on each side of a spillway involves separate fishways.

At a hydroelectric station, several fishways can be eventually connected to a single passage (collector gallery). Significant issues shad have in negotiating junctions or changing directions in the collecting galleries (which can result in the exit of the fish) must be taken into consideration when choosing to connect several entrances or install several fishways (see for example Reese, 2012 for salmonid). **It does not seem appropriate to connect more than 2 or 3 entrances to a single fishway**. If it seems necessary to have a greater number of fishways (structure of significant width, for example), we recommend the installation of several fishways. Special care must be taken when designing collecting systems. It is important to make sure there are no recirculation area, that internal velocities are homogenous (values ranging from 0.5 to 1 m/s can be proposed) and that turns are smooth. The installation of deflector(s) or guiding wall(s) to guide flows often improves fish guidance and must be thoroughly studied.

When fishways are already in place or when there are significant constraints, there are several possibilities for increasing the entrances' attraction. Without wanting to generalise, one possibility is to slightly move the entrance downstream so as to position it in a calm zone (see modifications made at Gate House, on the Connecticut, or tests at Lowell, on the Merrimack, where the entrance was extended downstream by the installation of a deflector).

A modification to the concurrent flows distribution can also be proposed. At a station, the prioritisation of units can result in fish coming close to the entrances, but without impeding their attraction. In most cases, the operation of the unit closest to the entrance should be limited (see Section 4.4.1.2). At a dam, creating a slot or implementing an adapted management of spillways (gates, valves) can improve the matter. Special attention must be paid to flow release methods (position of slots or devices – not too far, not too close; concentration of streams, etc.). If the installation of an entrance in a shad accumulation zone, such as corners, is impossible, one solution is to reduce or remove these zones (see the Holtwood example, on the Susquehanna).

5.4 FISHWAY SUPPLY FLOW

Even if it is not possible to establish a direct correlation between the flow rate in a migration fishway and its efficiency, since multiple factors impact these results (site configuration, hydraulic disturbance at the inlet, etc.), it is clear that the flow allowed into the fishway remains a crucial parameter (Katopodis & Williams, 2011; Williams & *al*., 2012). As laid out by Larinier (2000; 2002), Armstrong & *al*. (2010) or NMFS (2011), a migration fishway is more attractive when flow rates are greater than concurrent flows. This has been observed in the U.S. (Columbia, Susquehanna, etc.) where repeated observations have been conducted for migration rates in streams between structures: the greater the watercourse flow rate, during the shad migration period, the lesser the flow rates in the fishways, apart from discharges in bypassed sections. Subsequently, this results in weakened migration rates.

In general, due to limited budgets related to the size of structures to be built, and/or due to energy production losses, and at times, due to site-specific constraints, the flows available for migration fishways are limited. Two patterns emerge:

- facilities where watercourse flow rate is not of major use and for which only economic and construction constraints limit the availability of a required flow for a migration fishway;
- facilities where watercourse flow rate is of major use, mainly hydropower facilities, where flow rates for a migration fishway limit the energy production.

Various approaches have been proposed to determine the required flow rate for migration fishways. They are based either on watercourse hydrology or on concurrent flow rates.

For approaches based on hydrology, in the United States, NMFS (2011) recommends minimal flows corresponding to 3% of the mean annual discharge to be harnessed in the fishways for very large watercourses, such as the Columbia and Snake rivers. For smaller watercourses, but whose mean annual discharge exceeds 30 m^3/s (approx.), values between 5 and 10% of high water flows (Q_{90}-Q_{95}) are recommended. For even smaller watercourses, greater values can be considered. These recommendations are relevant to salmon whose upstream migration capacity is greater than the shad's.

In Great Britain and Wales, Armstrong & *al.* (2010) recommends a minimal flow corresponding to 5% of the mean annual discharge, and if possible, greater or equal to 10%. In France, Larinier & *al*. (1994) indicates that on watercourses as large as the Garonne or Dordogne (mean annual discharge of several hundred m^3/s), attraction flows corresponding to about 10% of the watercourse's minimum flow and of 1 to 1.5% during the fishway's maximum operational flow (about two times the interannual mean discharge) can be satisfactory.

For approaches based on concurrent flows, and especially for hydroelectric stations, Larinier & al. (1994), Towler & *al* (2013) and Orvis & al., (2016) use values ranging from 1% and 5%, and between 3% and 5%, respectively, of the maximum turbined flows. Armstrong & al. (2010) recommends values between 5% and 10%, the higher percentages applying to smaller structures or when fishways are poorly positioned.

Given the progress to be achieved in terms of shad fishway efficiency, we recommend allowing flows (including attraction flows) corresponding to a minimum of **3% to 5% of the concurrent flows**.

Since it is necessary, in the vast majority of cases, to ensure an operation of fishways corresponding up to twice the mean annual discharge, **the sum of flows allowed in the fishway must correspond to 6% to 10% of the watercourse's mean annual discharge.** For example, for mean annual discharges of 30, 50, 100, and 200 m^3/s, we recommend supply flows for fishways of 2-3 m^3/s, 3-5 m^3/s, 6-10 m^3/s and 12-20 m^3/s, respectively. It will be possible to increase or decrease these values for either smaller or very large watercourses.

For fishways located near hydroelectric stations, the concurrent flow to be taken into account is the maximum turbinated flow during the shad migration period.

For fishways located at the end of a bypassed section or near a dam (same level as a plant), they must be sized in relation with the concurrent flow for the maximum targeted operational flow (about twice the mean annual discharge or Q_{95} of the migration period). The minimum flow shall be about 1.5 m^3/s in all cases (see Section 5.6).

Apart from a flow percentage compared to watercourse hydrology or concurrent flows, it is important to keep in mind that the actual value of flow going through the entrances, which is directly connected to their size, is crucial. Various recommendations on size and flow velocity in entrances can result in flow values greater in smaller watercourses (see Section 5.6).

At hydroelectric stations, in order to limit production losses, a part of the fishways' attraction flows can be turbinated or pumped from downstream. Their injection, generally in the downstream section of structures, must be studied (see Section 5.5). A decrease of provided flows for the upstream migration can be considered outside the migration period of shad or other affected species.

5.5 INJECTION OF ATTRACTION FLOWS

Generally, flows required for fish migration do not all go through fishways so as to limit the construction cost of structures. Complementary attraction flows are injected downstream. When adding the attraction flow it is recommended to execute the flow injection at the end point of the fishway and not in the close by area.

In order to avoid disturbance of fish progression inside the fishway, the injection procedure is particularly important. Larinier & *al.* (1994), Larinier & Travade (2002), NMFS (2011) and Orvis & *al.* (2016) provide detailed information on the matter. A brief summary follows:

→ the attraction flow should be injected through a grid to prevent fish from being trapped in the stilling basin. The injection can be done through a bottom diffuser or through a lateral diffuser. In France and in Europe, the use of lateral diffusers is more common due to easier maintenance of the grid;

→ to avoid hydraulic disturbances (heterogeneous speeds, ascent, etc.) and limit the effects of aeration, the energy of the attraction flow has to be well dissipated on the upstream side of the injection point;

→ the location of the injection grid must help guide fish towards the upstream side of the fishway;

→ in order to not disturb the natural behaviour of fish, the water velocity through the injection grid must remain sufficiently low (< 0.3 to 0.4 m/s) compared to the water velocity in the fishway;

→ the free space between the bars of the grid depends on the size of the fish likely to go through the fish passage: 3 cm for large salmon and shad; less for smaller fish.

Recent studies on salmonids and cyprinids, in areas around the Gambsheim fishway (on the Rhine) have revealed that the injection of an attraction flow in a fishway represents an obstacle for fish migration. This is despite observing the recommendations listed above and especially when the injection gates are sealed (Travade & *al*., 2013 ; Tetard & *al*., 2014).These results show that better conditions can be achieved when the attraction flow is divided into several points of injection along the fishway. This promotes a flow coming from upstream rather than flow coming from the injection. For example, instead of injecting all the attraction flow in the last basin, 1/3 of the attraction flow can be injected in the penultimate basin and the remaining 2/3 can be injected in the last basin. This kind of injection system was designed in the Gerstheim fishway (on the Rhine). A divided system is a good way to limit the number of shad exiting the fishway, particularly when injecting substantial flow rates (> 5 m^3/s).

It is important to keep in mind that while a divided system like this reduces the civil engineering of the fishway, it also requires extensive maintenance for it is crucial to keep the injection gates clean.

5.6 HYDRAULIC CONDITIONS AND DIMENSIONS OF ENTRANCES

In the majority of cases, the flows coming from the entrances must be directed downstream, in the direction of the main flows, to limit stream shear caused by competing discharges (specifically turbines), which can greatly reduce their attractiveness. It is very important that this be monitored vigilantly as the flows mobilised in the fishways cannot generally counterbalance these phenomena. However, in hydraulically calm areas, a high or even perpendicular to flow inclination could be considered (recessed areas, area above the turbine draft tubes, etc.).

At the entrances, what is needed is to ensure streams that are wide and fast enough to attract fish to the fishways. We recommend velocities of 2 m/s regardless of the type of fishway. At the fish ladder or lift entrances, this means fall heights of about 0.20 - 0.25 m.

The main difficulty resides in maintaining the recommended velocity at the entrances throughout the fishway's operational range, given the variations in downstream water levels whose elevation for high flows can increase the flow sections at the entrances and thus reduce the velocities.

The recommended velocity can be maintained by:

- → increasing the flow transiting the entrances concurrently with the downstream water level. This occurs when the upstream water level is not regulated and rises at the same time as the downstream water level (besides structures subject to tides). The flow increase is even more important since the fishways have wide hydraulic sections, such as rockfill ramps. Depending on the fishways and the evolution of upstream and downstream water levels, this could help or even be sufficient to maintain the recommended velocity at the entrances. On the other hand, the fishways' flow does not increase when the upstream water level is regulated, specifically by hydroelectric power plants. In this case, the flow at the entrances can be increased by putting in place systems to regulate this eventually controlled flow;

- → the installation of a lift gate at the entrances to control the flow section. This solution is mainly aimed at fish ladder or lift entrances. The gate system is thus usually controlled so as to maintain the target fall (0.20 - 0.25 m). This requires the installation of two level probes, one installed upstream from the gate in the fish ladder and the other in the tailbay near the entrance.

Maintaining the velocity at the entrance is even more important given that the proportion of flow passing through the fishway compared to the watercourse flow is low and tends to go down towards high flows. Conversely, in cases where the proportion of flow passing through the fishway remains high, maintaining velocity at the entrance seems to be less of an issue.

It is highly probable that the entrances' dimensions are particularly important for shad due to their moving in schools and the difficulty they have entering the fishways. Even if, based on current knowledge, it seems difficult to define very specific criteria, various recommendations are made in the literature. The case of fish ladder and lifts entrances, generally narrow and established alongside obstacles with significant downstream depths, as well as that of entrances to ramps or bypass rivers, generally wide and established alongside obstacles with shallow downstream depths, are exceptions.

For pool and weir fishways and lifts entrances, Quinn (1994) recommends for the shad respective minimum widths and depths of 1.2 and 1.8 m. These recommendations were reiterated by NMFS (2011) for large salmonid. Orvis & *al*. (2016) sets forth minimum respective widths and depths of 1.2 and 0.6 m, regardless of species. However, these parameters depend on the flows that can be allowed in the fishways and the structure's characteristics, especially the downstream depth of the watercourse.

Beyond these elements taken from the literature, some study results tend towards increasing the widths and depths of the entrances: the swimming depths of most shad monitored at Lowell, which were greater than 1.5 m (ALDEN, 2011), the deep swimming in the Golfech tailrace (Belaud, 1985), and the monitored rates of shad entering the locks (Normandeau Associates Inc., 2003), wide and open, which were high. For salmon, on the Columbia, Reese (2012) notes that fish favour entering the fishways via the largest entrances (and those with the largest supply of water) and suggests that fish are more hesitant faced with smaller entrances.

As a precaution, we recommend minimum respective widths and depths for the entrances of 2 m and 1.5 m. Under these conditions, and taking into account the other criteria previously accepted, it is possible to state a minimum supply flow of 6 m^3/s per entrance.

On smaller watercourses where one cannot achieve this level of flow for the fishways, these dimensions can be reduced while striving to maintain a width / depth ratio for the entrance approaching 1, so as to achieve a “square” stream likely to reach the furthest downstream possible. To maintain a clear surface stream, considering the target fall value (0.20-0.25 m), the entrance’s depth must not be less than 0.7-0.8 m. The width should also be a minimum of around 1 m. Under these conditions, the minimum flow to be achieved at the entrance is 1.5 m^3/s.

A gradual transition from the bottom to the entrance of the fishway is likely to improve the guiding of fish and must be studied (DVWK, 2002 states a maximum slope of 50%). It is however often difficult to implement this on large watercourses, especially at hydroelectric power plants.

The **joint or rockfill ramps** are generally wide and installed alongside obstacles with shallow downstream depths. Thus in most cases, their entrances do not need to allow a width different from the rest of the fishway. For bypass rivers, however, it is possible to pinch the flows at the entrance. The recommended bottom-to-entrance gradual transition is often easy to implement on this type of fish ladder.

5.7 DESIGN AND SIZING OF FISHWAYS ADAPTED TO SHAD

It should first be specified that certain types of fishways are not suitable for shad.

This is especially the case for baffle fish ladders, regardless of the type of baffles. Even if for moderate slopes, they can allow the passage of a certain number of shad, they do not seem to show high enough efficiency due notably to the presence of helical currents and highly-aerated waters (Quinn, 1994; Larinier & Travade, 2002; Orvis & *al*., 2016).

For Borland type fish locks, data on the shad are fragmented. However, numerous fishways have shown overall low effectiveness, both in the United States and Europe. The first locks built on the Columbia River were even replaced with fish ladders (Larinier & Travade, 2002). This type of fishway cannot be recommended for shad, considering their exacting requirements.

Hereinafter will be presented a summary of the main design guidelines and sizing criteria for the types of fishways adapted to the passage of shad. Following that, elements regarding the choice of type of fishway according to the site’s characteristics will be provided.

5.7.1 FISH LADDERS

The principle of fish ladders is to divide the total fall into multiple passable falls, separated by basins which allow the fish to rest (Figure 5-1). The recommendations made hereinafter are mainly derived from Larinier & Travade (2002) and Orvis & *al*. (2016) as well as a variety of available feedback (see Section 4.4.2.2).

As the only way shad can pass from one basin to another is by swimming, the communication between the basins must be deep enough to obtain a surface stream. Of the various modes of communication, submerged orifices are recommended, as the shad tend to stay trapped in counter currents located on the surface over the orifices (Monk, & *al*., 1989). The alternate deep slots could allow passage but as soon as the flow in the fishway allows, vertical slots (> 0.75 m^3/s), or even double vertical slots (> 1.5 m^3/s), must be favoured.

Taking into account the passability by small species, including benthic ones, leads to the installation of deep slots which reach the bottom of the basins (without weir) as well as roughness at the bottom of the basins.

The main fish ladder sizing criteria involve:

- the fall height between the basins. For the shad alone, the recommended fall is 0.25 m, with a maximum of 0.30 m, that is maximum velocities in the streams of 2.2 and 2.4 m/s. However, taking into account passability by smaller species often leads to installing falls of about 0.20 m;
- the type of stream which must be a surface type. This means that the upstream supply must be greater than twice the fall height. On this point, Ice Harbor type fish ladders, even modified, are not satisfactory;
- the width (b) of the communications (slots or notches) which much be a minimum of 0.40 m, and increased to 0.45-0.50 m as soon as the flow in the fishway allows;
- the dimensions of the basins: a minimum length of 3.5 m and a minimum width of 2.5 m are recommended with regard to the schooling behaviour of shad. Criteria are also given to obtain a proper organisation of the flows in the basins. For the vertical slot fishways, the basins' length is generally 7 to 12 times b. For a basin length of 10 b and a fish ladder slope of 5%-7.5%, a width equal to 7-7.5 b could be adopted so as to obtain a 2-recirculation zone flow topology and avoid the jet impacting the side opposite the slot. For different basin lengths, one can recommend keeping a same width / length aspect ratio (0.7-0.75). In the case of double-slot fish ladders, the basin widths are usually 9 to 10 times b;
- the average water height in the basins with a minimum value of 1.0 m, reaching 1.2 m once the flow in the fishway allows;
- the maximum dissipated power in the basins which must not exceed 150 W/m^3.

Under these conditions, for a single-slot fish ladder, minimum supply flows in the fishways must be 0.75 to 1 m^3/s and the minimum volumes in the basins between 10 and 12 m^3. For a double-slot fish ladder, these values reach 1.5-2 m^3/s and 20-24 m^3. Beyond this, Orvis & *al*. (2016) recommends basin volumes equal to 5 L per kg of fish, thus for the European shad, 10-15 L per fish. Under these conditions, and based on the rate of migration seen by Chanseau & *al*. (2000) – on average, daily and hourly passage peaks are on average 10% of the annual passages and 12% of the daily passages. Thus basin volumes of 12 m^3 should allow annual passages of around 100,000 fish.

Fish ladders have the advantage of being configure as a serpentine figure, greatly facilitating their installation. However, given the difficulty shad have to move through the turning pools, it is recommended to avoid or at least limit as much as possible the number of curves in the fish ladder. Special care will be given to designing the turning pools so as to retain a basin length with regard to the upstream barrier and rounding or cutting the angles. The shad's passage through these basins can eventually be improved by preventing fish from accessing areas where they become trapped (Dartiguelongue & *al.,* 1992 ; Larinier & *al.,* 1994).

The advantage of the vertical slot fishways is that they adapt well to variations in the upstream water level. As the transiting flows and basin volumes evolve similarly, the power dissipated in the basins remains fairly constant.

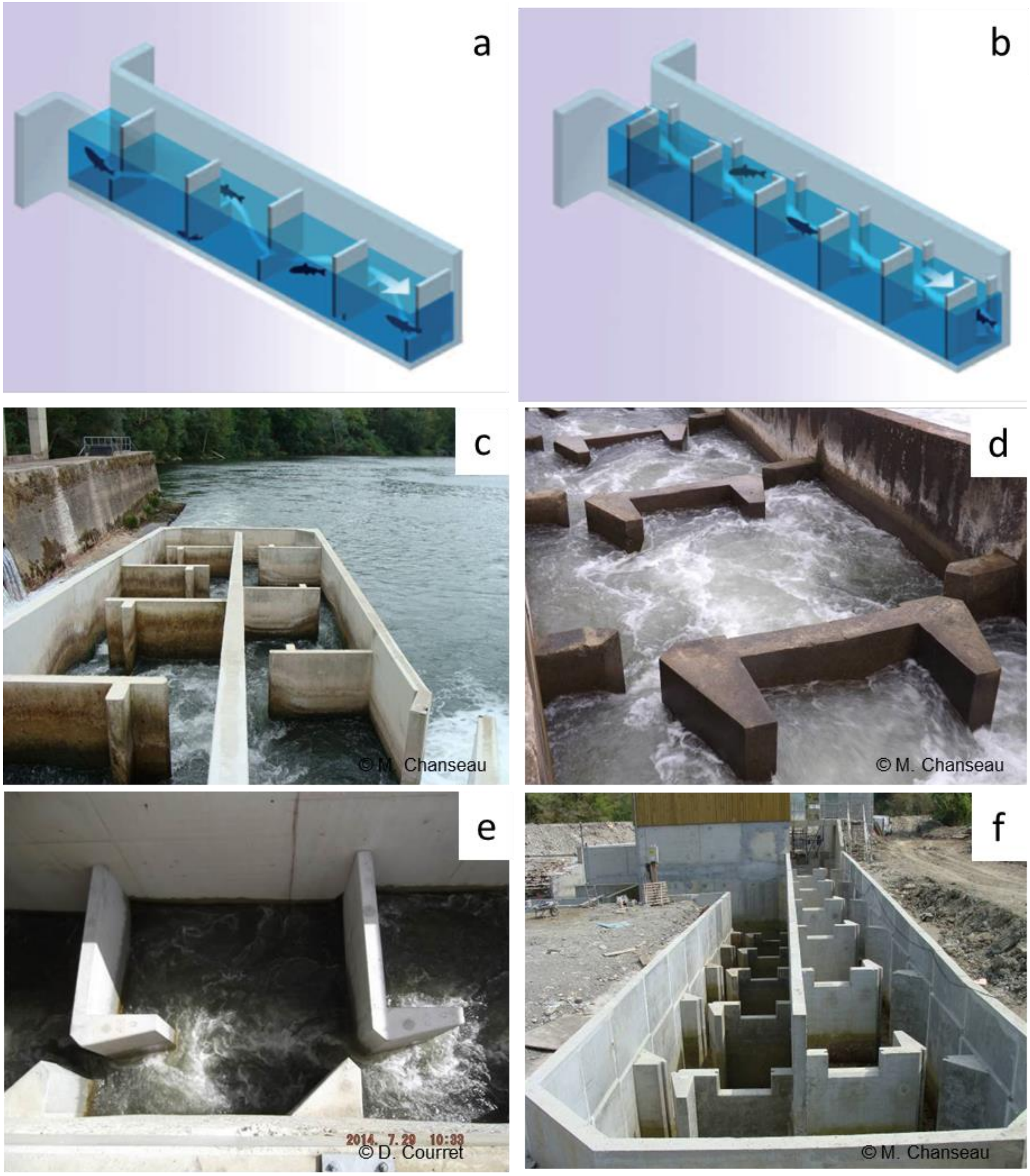

Figure 5-1 a) and b) Schematic representation of lateral alternate notches and vertical slot fish ladders (figures from Baudoin & al., 2014). c) Lateral notches ladder at Montans – Saint Sauveur weir on theTarn. d) Double vertical slots ladder at Augreilh on the Adour. e) Simple vertical slot ladder at the Cavaletade weir on the Garonne. f) Turn at the vertical slot ladder, Masseys plant on the Gave d'Oloron.

5.7.2 PRE-DAM

Pre-dam constitute a variation on fish ladders in which partitions are formed by several walls or weirs creating large basins downstream from the obstacle and breaking up the fall to be travelled. This type of fishway is generally installed on structures with small fall heights, 1.0-1.5 m. If their dimensions are largely comparable to those of fish ladders, the flows mobilised are generally greater and there can be criteria that exceed somewhat the recommended values (Larinier & al., 1994), with regard to most notably the power densities dissipated, the basins often being large and the number of falls to pass reduced. As the communications between basins are sometimes shallow, it is important to ensure a surface stream is obtained.

5.7.3 "NATURAL" OR ROCKFILL FISHWAYS

"Natural" or traditional migration fishways serve to connect the headrace and tailrace thanks to a more or less wide channel where energy is dissipated and flow rates are reduced by the roughness of the bottom and walls, and/or reduced by a series of singularities more or less evenly distributed. Recommendations will be taken from Larinier & al. (1995), Lariner & al. (2006), Cassan & al. (2014) and Tran (2015). It should however be noted that there is still very little known about the efficiency of these installations for shad (Haro & al., 2008).

Four different types of fishways can be distinguished:

- joint rockfill ramps (bottom roughness only);
- ramps with evenly placed blocks;
- ramps with periodic rows of blocks;
- bypass rivers.

JOINT ROCKFILL RAMPS (BOTTOM ROUGHNESS ONLY)

These ramps are composed of fairly uniform-sized blocks placed against each other and forming a rough passage. They do not really provide rest areas for fish, which means that they must be overcome in one go, by sprinting or sustained swimming. The length of these ramps depends on the swimming and stamina of fish.

The ramp's slope, block characteristics (size, position and jointing) and flow per metre of width are parameters that determine the ramp's flow characteristics.

For shad, it is recommended to maintain a minimum water depth of 0.4 m and not to exceed a mean flow velocity of 2.5 m/s over a distance of 10 m, or 1.5-1.8 m/s over a distance of about 20 m.

These velocity limits are reached for slopes of 8-10% and 5%, respectively, which means that overcoming the ramp is possible for unit flows between 0.5 and 0.8 $m^3/s/m$ and between 0.4 and 1 $m^3/s/m$. In all cases, this type of fishway only compensate falls of a maximum of 1 m.

The benefit of these ramps is that they are low maintenance and can allow substantial flows. In most cases, the installation of a lateral weir is essential to adapt to the upstream water level variations. In order to limit risk of flow concentration in the lowest point of the ramp, it is recommended that the lateral weir slope be less than or equal to the longitudinal slope.

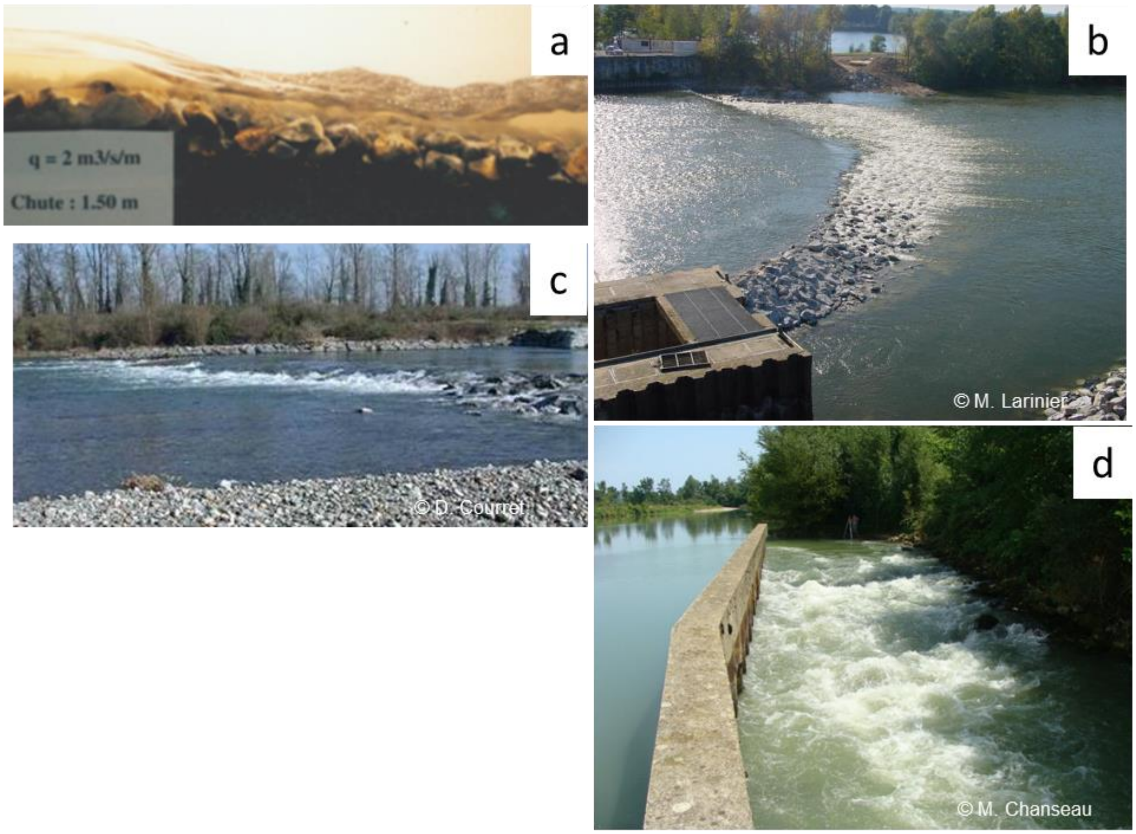

Figure 5-2 **Pictures of joint rockfill ramps. a) Study on scale model (from Larinier & al. 1995). b) Ramps forming pre-dams at the Saint-Laurent weir. c) Passable weir, design by Lescar on the Gave de Pau. e) Ramp at the Toulouzette weir on the Adour.**

RAMPS WITH EVENLY PLACED BLOCKS

In this configuration, the energy is dissipated through singularities made by isolated blocks regularly distributed on a coarse ramp in staggered rows (longitudinal and diagonal space between adjacent blocks). This results in a so-called uniform flow in the fishway without marked hydraulic singularities (local fall, marked hydraulic jump, insufficient water depth) which could cause issues to the upstream migration of fish. The water line is roughly parallel to the ramp. Each block generates a trail which represents a resting area for fish and allows them to overcome a maximum length of the ramp (Figure 5-3).

Parameters defining the flow characteristics on the ramp (velocities and water depth) are the ramp's slope, the concentration and characteristic dimensions of blocks (protruding height of blocks above the ramp, width facing the flow and form of blocks) and flow per metre of width.

The blocks generally have a width (facing the flow) of 0.4 to 0.6 m (up to 0.3 and 0.7 m) and protruding height of about 0.4 to 0.6 m (up to 0.8 m). Concentration of block is generally close to 13% (axis to axis spacing equal to 2.8 times the width of the blocks) and can reach 15-16%. No need to exceed that percentage since it does not significantly reduce velocities (Tran, 2015) but does however increase the risk of blockage.

It is important to have a bottom roughness composed of small blocks (0.10 to 0.25 m) in order to reduce flow velocities.

For shad, it is recommended to maintain a minimum water depth of 0.4 m and not to exceed the velocity of streams between blocks of 2.0 m/s and a dissipated energy of about 300-450 W/m^3. The recommendation of greater dissipated energy than in the fish ladders is connected to the very different organisation of flows between the two types of fishways, with a lower ratio between maximum and output velocities in the block ramps.

These criteria mean slopes that cannot exceed 5-6% for shad, with a possible fishway passability for unit flows ranging from 0.3 to 0.6 m^3/s/m (Larinier & *al*., 2006). Slopes of 4-5% are to be considered when taking into account other holobiotic species. These recommendations correspond with the Haro & *al*. (2008) passability test results.

When blocks are submerged, a high-velocity flow is formed above, which causes a significant increase in velocities and agitation levels between blocks. Therefore, it is considered that areas where blocks are submerged are not suitable for fish migration. It is recommended to maintain, for the entire targeted operation range, a section of the ramp where blocks are not submerged (a minimum width corresponding to a flow pattern: 2 to 3 times the width of the blocks (1-1.5 m).

Adaptation to upstream water level variations can be done by:

- choosing blocks high enough so that they emerge from the water even at the maximum upstream water level. Adjustment possibilities are limited to water level variations of 0.2-0.3 m given the minimum water depth to maintain (0.2-0.4 m depending on species) and the maximum block height (manufacturing, stability and blockage constraints [0.6 or 0.8 m]);

- in most cases, by installing a lateral weir. It is recommended, like for the joint rockfill ramps, that the lateral weir slope be lower or equal to the longitudinal slope. However, it seems possible to use slightly higher values without really having an impact on the flows, up to some ten percent for short ramps (low falls). The installation of a lateral weir is interesting for the fishway’s attraction; sharp increase of supply flow transiting when the upstream water level increases and floods the low section of the ramp.

Generally, the width of ramps with evenly placed blocks built in France range from 2.5-3 m to 12-15 m. Supply flow for the minimal upstream water level (low water) range from 0.2-0.3 m^3/s to several m^3/s. These flows are generally multiplied by a factor of 3 to 5 for the maximum upstream water level (2-3 times the mean annual discharge).

Rocks chosen in quarries were first considered to make up the roughness; however their size and shape cannot be controlled. This is why two sets of flow equations, for blocks with flat upstream face and rounded upstream face, were produced so as to resolve the uncertainty regarding the shape of rocks (Larinier & al., 2006). In France, given that it is difficult to find the required number of blocks in quarries, it is more and more common to use prefabricated blocks whose shape can be controlled. To this day, there are no recommendations on the best shape (circular or rectangular) to be used for the migration of species (each with their own advantages and disadvantages). Upstream migration tests planned for 2017 and 2018 by Pôle Ecohydraulique ONEMA-IMFT should provide answers on the matter.

It is recommended that blocks ramps be straight and that possible changes of direction be at intermediate basins. For small slope, gradual turns with large curve radiuses can be considered. In the case of ramps exceeding a length of 30 to 40 m, a midway basin is sometimes developed to provide a bigger and calmer rest area than the rest areas provided by the wakes of blocks.

Flows can seem fairly aerated and questionnable for shad passage. The aeration level remains low and higher at the surface than in the baffle fishways.

The implementation of ramps with evenly placed blocks is generally limited to obstacles whose falls are less than 2-3 m (40 to 60 m of ramp at 5%), given that the significant size of ramps would entail high cost and installation problems.

There is no, as far as we know, monitoring to determine the efficiency of this type of shad fishway. However, Haro & al. (2008) and Franklin & al. (2012) carried out experiments on Alewife (Alosa pseudoharengus) at Town Brook and East River at fishways very similar to ramps with evenly placed blocks. Even if the behaviour of this species seems very different from the American and European shad's, it appears to be useful to briefly present the main results obtained. On the Town Brook River, the efficiency of the ramp (length: 32 m, mean slope: 4.2%) is 94%; almost 94% of fish reach the upstream on their first try. The median time in the fishway is of about 11 minutes. On the East River, two ramps, with slopes of 7.9% and 3.5%, were tested. Their efficiency is 71% and 99%, respectively.

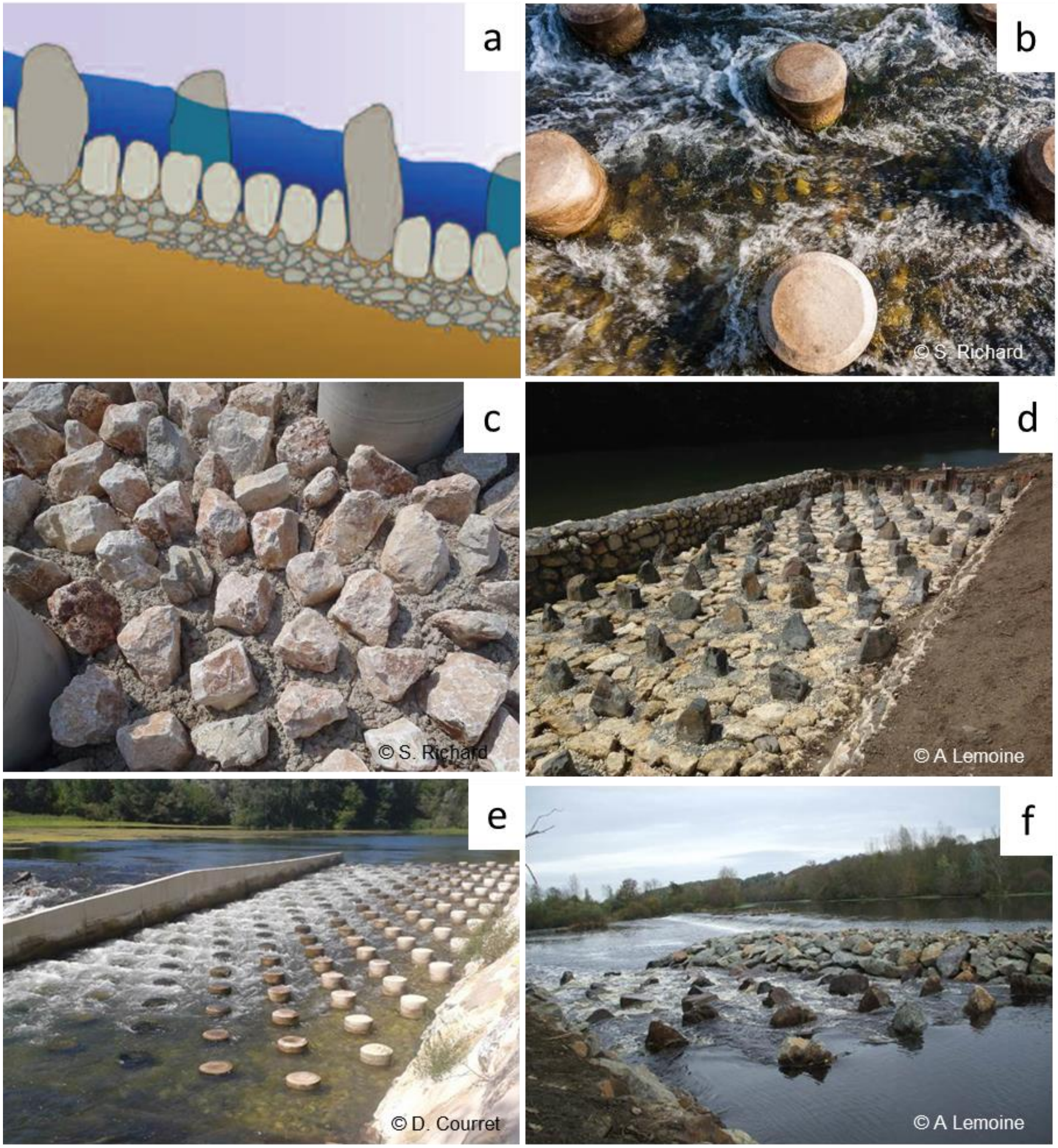

Figure 5-3 **Pictures of ramps with evenly placed blocks. a) Schematic representation of a longitudinal section (Baudoin & al., 2014). b and c) Details of flow and of bottom roughness. d) Bourg-Charente ramp on the Charente (without water). e) Malhaute ramp on the Orb. f) Gouex-Villar ramp on the Vienne.**

RAMPS WITH PERIODIC ROWS OF BLOCKS

Pseudo basins and falls between rows are made by placing rocks in rows at regular intervals. This type of fishway is very similar to a "classic" fish ladder and the design criteria are almost identical. The advantage of these fishways is that they can be developed in non-built environments with the possibility of having significant width.

Insofar as fishways are quite wide which helps reduce fish reluctance to enter, water depths in basins greater than the depth recommended for “classic” fish ladders can be considered. A minimum depth of 0.4 m is recommended for shad (same as for ramps with evenly placed blocks), with higher values if possible.

Since it is difficult to be precise for the porosity and cribbing of the various rows, a certain margin must be taken into consideration when designing falls between basins. This is why fishways designed so as to have falls between rows of 0.20 m are recommended for shad. Falls of 0.15 m should be considered for smaller species.

Sometimes links between basins are shallow; it is important to make sure a surface stream is obtained.

The regularly distanced row formations allow for general longitudinal slopes 1% greater than blocks ramps, i.e., up to 6-7% for shad. If other holobiotic species are considered, slopes of about 5% are to be chosen.

In order to adapt to the upstream water level variations, same as for the ramps with evenly placed blocks, changes in height of the blocks or the installation of a lateral weir can be considered.

Monitoring carried out on Cap Fear River, United States, on the Lock and Dam 1 site after the installation of a ramp revealed an efficiency rate of 50% for the American shad in 2013 and almost 70% in 2014 (Raabe & *al*., undated). The specific characteristics of the fishway are not available and only the mean slope value, between 3 and 5%, is specified.

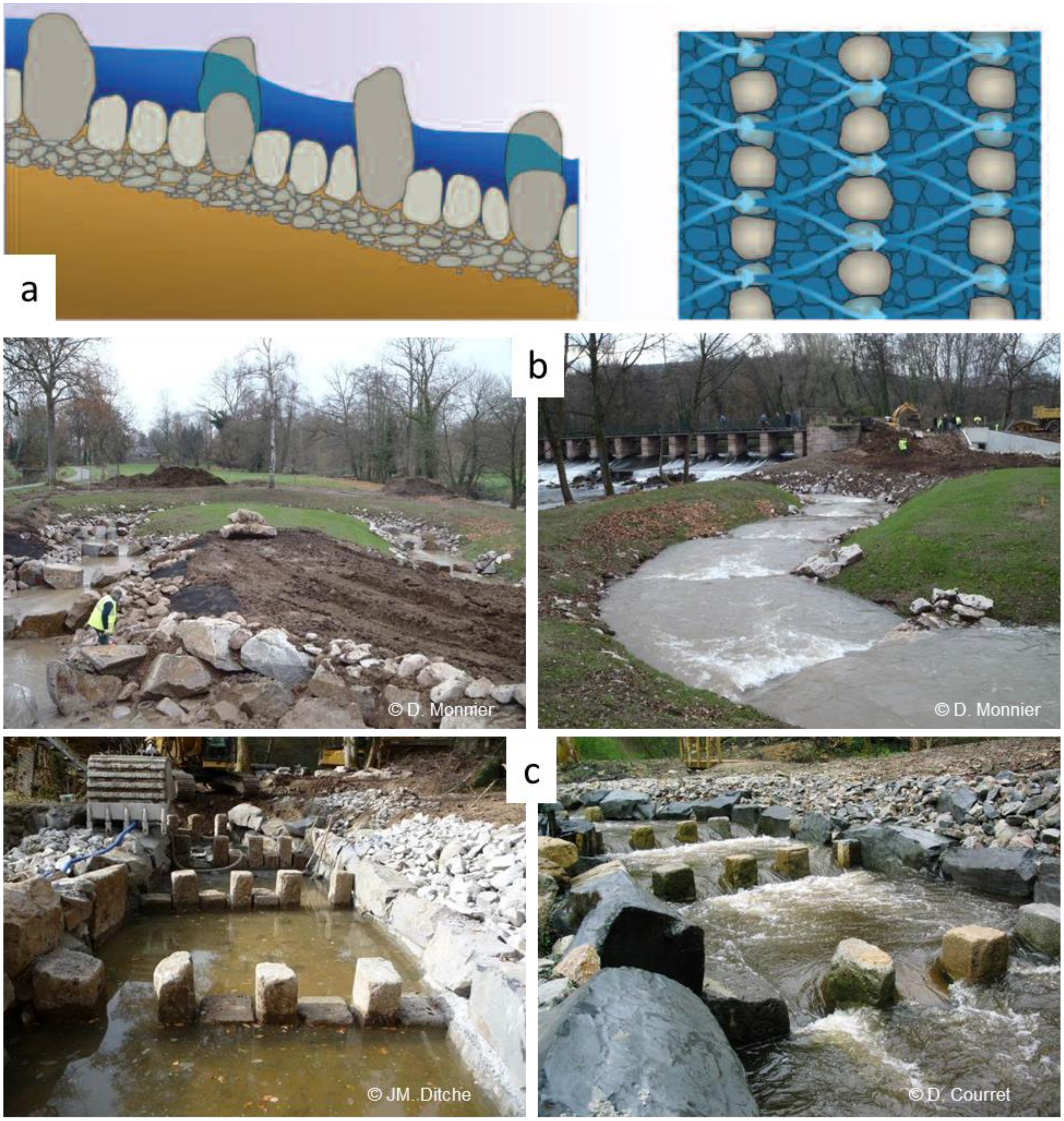

Figure 5-4 **Pictures of ramps with periodic rows of blocks. a) Schematic representations (Baudoin & *al*., 2014). b) Bypass river with periodic rows at Avolsheim on the Bruche. c) Bessette fishway on the Diège.**

BYPASS RIVERS

When there is no available space on the bank, the fishway can be a bypass channel.

If the gradient of the channel is greater than 3-4%, it is necessary to use a “strict” organisation of the structures, in the form of traditional fish ladders or evenly placed rockfill, so as to properly dissipate the flow energy and reduce velocities.

However, when it is possible to allow for a significant length and to lower the channel's gradient below 2-3%, we then have more liberty when it comes to the flow energy dissipation method and that way, getting closer to the flow of a river section (hence the term bypass river) (Figure 5-5). The energy can be dissipated thanks to bottom roughness and the shape of the channel (sinuosity), and singularities composed of lateral groynes and large isolated blocks. There is no properly established design criteria. Design can be done by analogy with existing bypass rivers or by using physical and digital modelling.

Flows going through the bypass rivers, and thus the channel sizes, can be significant and reach several m^3/s. If the fishway entrance is well positioned, it can become one of the most efficient types of fishway; fish do not seem too reluctant to enter (gradual transition, little containment effect) and have no or very little difficulty progressing in the fishway. It should however be ensured there are resting areas for fish when fishways are quite long.

The need for a considerable channel length for the decrease of the gradient could, in most cases, mean moving the fish entrance far downstream of the obstacle. However, placing the fish entrance near the toe of the obstacle is essential for good efficiency. If this is not possible with a bypass river, another type of fishway can be considered or the unsuitable position of the entrance can be balanced by the significant increase of flow in relation to concurrent flows.

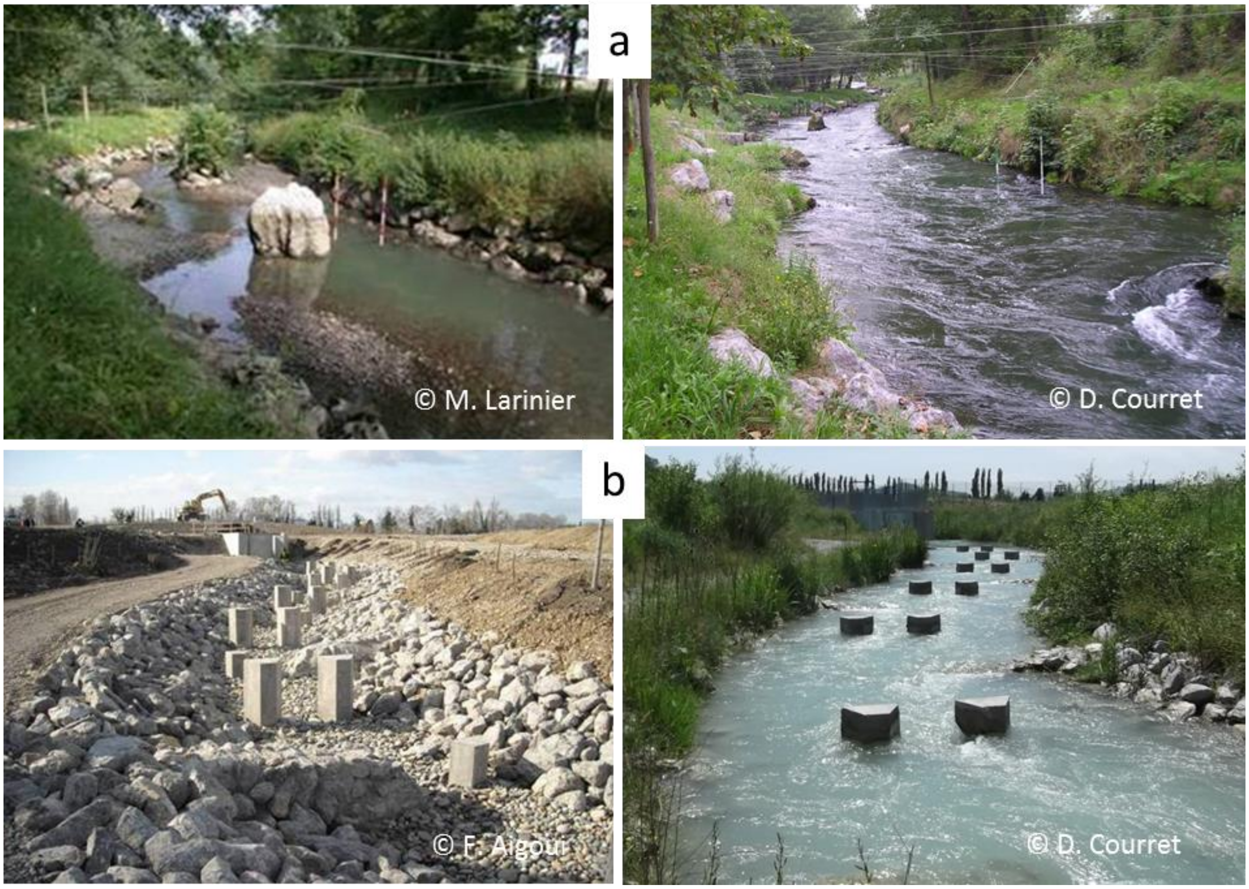

Figure 5-5 Pictures of low-gradient bypass rivers. a) Biron River on the Gave de Pau; b) Livron River on the Drome.

5.7.4 LIFTS

Essentially, a fish lift is a mechanical system which captures fish at the bottom of the obstacle in a basin with a sufficient amount of water considering the amount of fish. The basin is then lifted and discharged upstream. Fish are attracted to a holding tank by an attraction flow and are trapped there by a non-return device (Travade & al., 1992) (Figure 5-6 and Figure 5-7). The majority of the recommendations hereinafter were taken from Travade and Larinier (2002); and Orvis & *al*. (2016). (Travade & *al.*, 1992).

The most essential design and dimension points focus on:

→ The non-return device which traps fish (crowder):

The crowder is a device composed of 2 screens in a 'V' position forming a funnel with the tip towards the upstream (Figure 5-7). It is meant to help fish easily enter the holding tank and reduce the risk of them exiting.

The space between the two screens must be sufficient to limit fish reluctance, but not too significant so as to prevent their exit. Very different widths were observed at structures on the U.S. East Coast (between 0.3 and 1.0 m), but no ideal width was established (see Section 4.4.2.4). To date, a width of between 0.3 and 0.4 m seems suitable.

Velocities of between 0.6 and 1 m/s must be maintained inside the system so as to attract fish.

Configuration of the crowder is important even if there are no specific criteria for its design. We recommend a very gradual narrowing towards the upstream of the non-return device. Changes to the crowder system tested at Lawrence on the Merrimack (transformation of the initial 'V' system into a baffle by partially closing the 2 screens) could not be properly assessed.

In order to limit flow disturbances, it is recommended to orientate the components of the crowder towards the flow direction.

→ Water volume of the holding tank and the lifting tank (hopper), in relation with the lifting frequency:

Conditions for the holding of fish in trapping systems must be adapted to the fish's capacity and the fact that they move in schools, thus preventing fatigue and stress. There is a holding tank downstream of the hopper in most shad lifts because of the significant number of fish likely to enter the fishway. A crowder system (moving screens) helps bring fish into the tank before it is lifted.

To limit fish fatigue, flow velocities in the holding tank must remain beneath 0.5 m/s. The lift frequency must be rather high during the species migration period. Cycles of 15 minutes, and below 30 minutes at all times, can be considered (Travade and Larinier, 2002; Orvis & al., 2016).

The available water volume must be adapted to significant migration. Minimum volumes of 30 L per fish in the holding tanks and of 10-15 L per fish in the hopper must be ensured.

In order to properly design the fishways, it is important to be aware of the fish migration rhythms. In France, Chanseau & al. (2000) pointed out that at the Golfech (Garonne) and Tuilières (Garonne) lifts:

→ daily peaks represent respectively on average 9.9% (min: 6.7% ; max: 20%) and 11.5% (min: 5.1%; max: 21.4%) of the annual migrations;

→ hourly peaks represent respectively on average 12.7% (min: 9.7%; max: 14.7%) and 12.6% (min: 8%; max: 20.5%) of maximum daily fish counts.

In the United States, analyses carried out as part of this report reveal that maximum daily passages represent an average of 7.2% (min: 4.6%; max: 10.4%) of the annual migration (passages observed in the fish ladders of the Bonneville (Columbia River) structures for the 2006-2015 period during which more than 22 million shad were counted). At Holyoke, on the Connecticut River, the maximum daily passages represent an average of 9.8% (min: 5.8%; max: 16.6%) (for the 1976-2015 period during which more than 12 million of shad were counted).

Thus, it seems possible to consider, in most cases, a maximum daily migration representing about 10% of the annual migration and an hourly migration representing 15% of the maximum daily migration for the design of the fishways. In these conditions, for a 15-minute cycle, volumes in the holding tank and the hopper must be 11 m^3 and 4 m^3, respectively, in order to ensure satisfactory migration conditions for 100,000 fish. However, Travade and Larinier (2002) recommend minimum holding tank dimensions of 5 m x 2.5 m x 1.5 m, i.e., a volume of 19 m^3.

Water injected into the holding tank must be poorly aerated (see attraction flow injection at Section 5.5) and flow rather undisturbed. Risks of injuries must be minimised (mobile parts) and protruding angles must be banned. As indicated by NOAA (2012), it is important to limit noise and vibrations in the structure and to maintain sufficient luminosity. The shape of the tank must be optimised so as to allow quick exit of fish.

Numerous parameters are likely to influence the decision to install a lift. The height of the falls and the banks configuration (available right-of-way) near the lift's installation are the key parameters. In France, and the United States (Haro, com. pers.; NOAA), it is generally considered that a lift is the best fishway for falls greater than 8-10 m (for both biological and financial reasons). However, it is essential to keep in mind that lifts require significant maintenance.

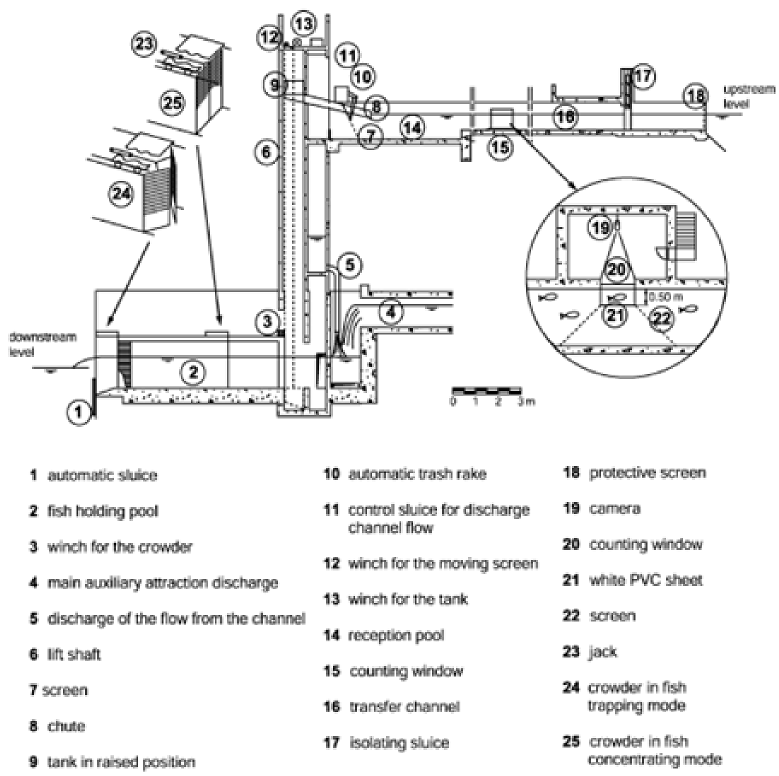

Figure 5-6 Illustration of a lift. Schematic representation (from Travade & Larinier, 2002).

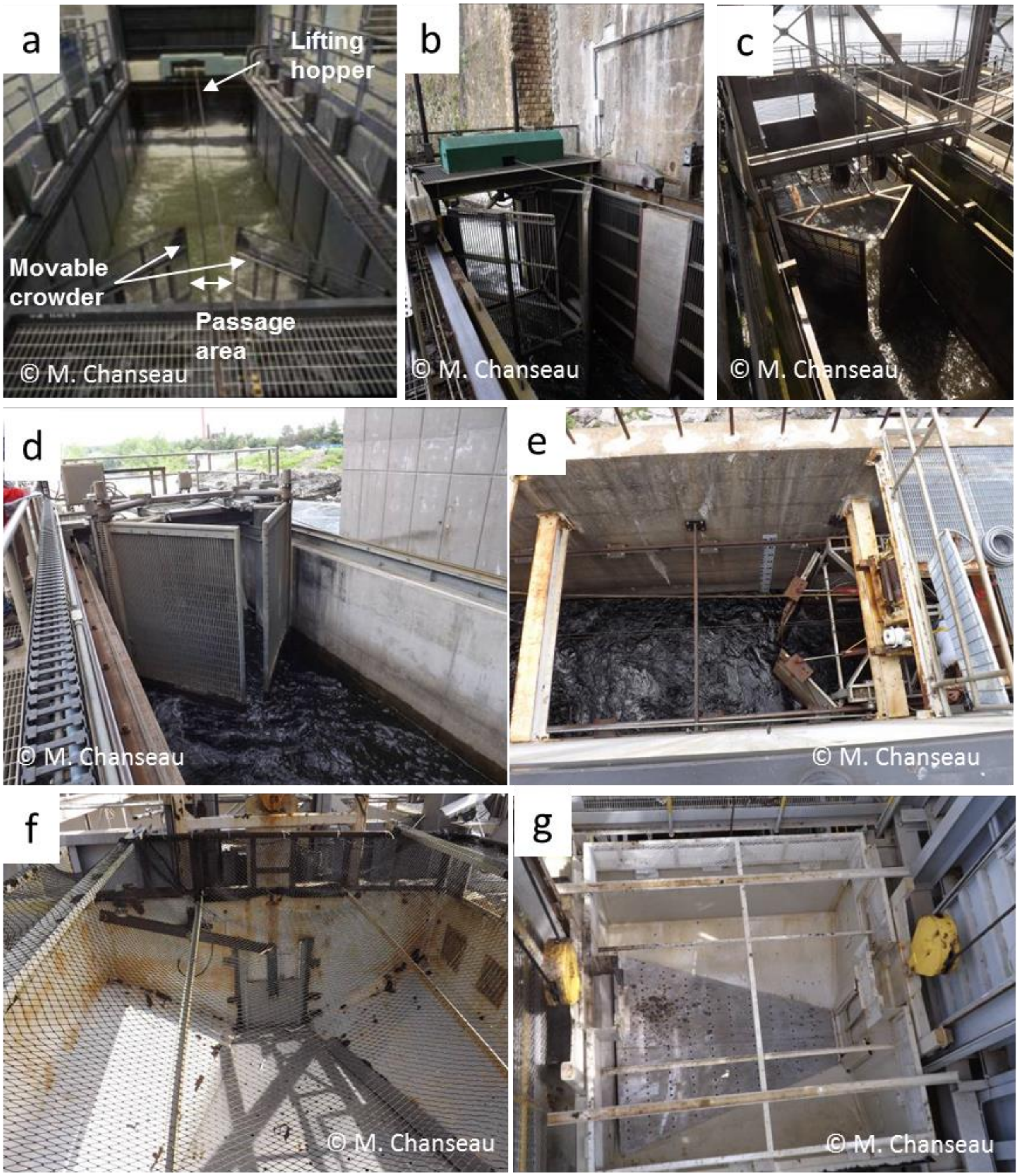

Figure 5-7 **Pictures of lifts (passage area, non-return device, holding tank and lifting tank); a) Golfech on the Garonne; b) Tuilières on the Dordogne; c) Conowingo on the Susquehanna; d) Holyoke (plant) on the Connecticut; e) Lowell on the Merrimack; f) Tank at Conowingo; g) Tank at Holtwood on the Susquehanna.**

5.7.5 NAVIGATION LOCKS

In 1992, François Travade and Michel Larinier (Travade & al., 1992) pointed out that navigation locks, whose operation is similar to the lift's, could be a suitable support, or interesting alternative to the construction of a fishway on existing structures, provided their management is adapted.

Studies recently carried out and presented as part of this work, especially in France and the U.S., reveal efficiencies of less than 20% to more than 80%.

The following conditions must be complied with in order to obtain good efficiency:

- the fishway must be located at the right place on the structure and must not start too far downstream from the obstacle;
- the attraction flow, often provided by the filling valves, must be sufficient in relation with the concurrent flows;
- the number of cycles must be sufficient, which is often a problem given constraints related to fluvial navigation.

Fish sometimes seemed to have a hard time staying long enough in the fishways during the attraction phase (especially on the Cape Fear River, at Lock and Dam 1). This problem can be reduced by a modification of the opening of the downstream gates or an increase of the number of cycles.

In the majority of cases, not all conditions were met and did not indicate there would be a sufficient efficiency of the locks. Constraints related to fluvial navigation, often a priority in relation with fish constraints, limit the interest of using this type of fishway. However, the use of the existing locks was the best option on certain watercourses such as the Rhône (Larinier and Chanseau, 2009).

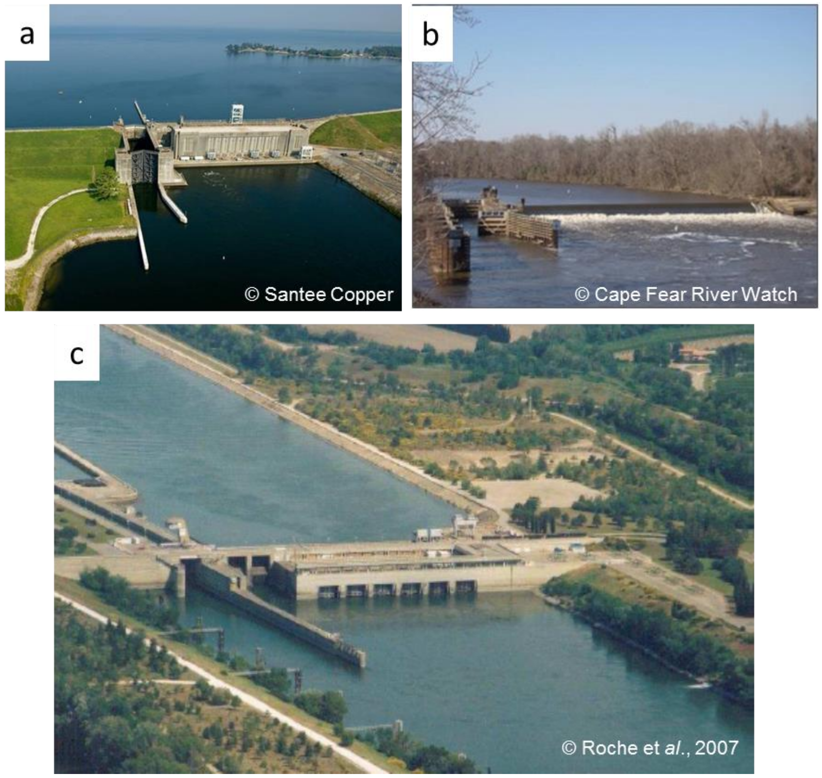

Figure 5-8 Pictures of navigation locks. a) Pinopolis Lock on the Cooper River (USA); b) Lock and Dam 1 on the Cape Fear River (USA); c) Beaucaire Lock on the Rhône (France).

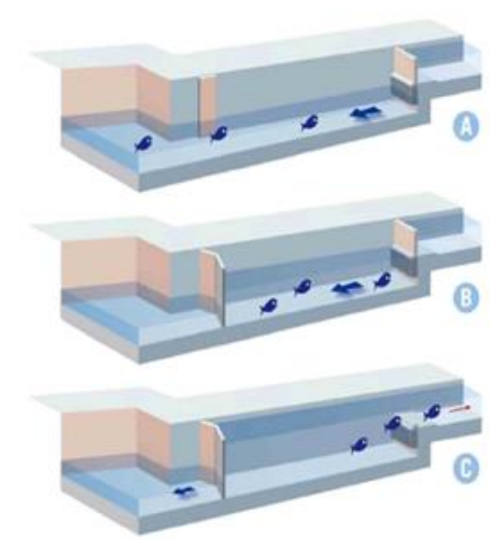

Figure 5-9 Navigation lock operating principle for the migration of fish. Rhône locks example (Zylberblat & al., 2011). a) Attraction of fish; b) closing of gates; c) exit of fish.

5.7.6 CHOOSING THE TYPE OF FISHWAY

The selection of the type of fishway must take into consideration numerous parameters:

- → pre-defined location of the fish entrance(s), and space available in the area;
- → supply flow of the fishway;
- → height of fall to be overcome;
- → upstream and downstream water level variations depending on the hydrology, for the selected operation range.

The position of entrances and supply flows are a determining factor of attraction and efficiency of the fishway: the fishway best suited to complying with the selected objectives will be chosen. Given the space constraints (necessity for the fishway to start near the exit of the turbines), fish ladders or fish lift are generally chosen for hydroelectric stations. If it is impossible to properly position the entrances, the increase of the fishway's supply flow shall be considered.

In general, lifts are considered to be the most suitable for shad when the height of a fall is greater than 8-10 m. Lifts help reduce costs and prevent fish from crossing significant lengths and too many falls which could reduce their efficiency (see Section 4.4.2.2.). Fish ladders must be favoured for lower falls, since lifts require significant maintenance. Fish ladders are adapted to a large range of heights. More "natural" fishways or rockfill must be limited to low falls given that they need a lot of space. For ramps with evenly placed rockfill or successive weirs, a maximum height of 2 to 3 m can be considered in the majority of cases. Rockfill ramps shall be limited to heights lower than 1 m. Low-gradient bypass rivers, can be implemented for structures with considerably greater heights (provided there is space on the banks).

6 CONCLUSION

Obstacles built on watercourses have a significant impact on shad migration. As stated by Larinier and Travade (1991; 2002), an efficiency of 75% is exceptional; 50% is excellent; 10-20% far too common.

The recommendations found in this report are meant to at least make the achievement of the best efficiency obtained so far (70 to 75%) a general occurrence, and if possible obtain greater efficiencies. These recommendations are mainly based on the documents of Larinier and Travade (2002), NMFS (2011), Towler & al. (2015), and Orvis & al. (2016), but also on the information acquired thanks to the document review carried out as part of the present work and following site visits and exchanges during the spring of 2015 on the U.S. East Coast.

Given their short migration period, the fact that they move in schools, and their exploratory capacities which are far more limited than other species such as the salmonid, it is essential to allow shad to easily and quickly find the fishways, enter them with minimum reluctance and move through them without constraint. To do so, it is important to:

- → **harness significant flows** in fishways corresponding to a minimum of 3% to 5% of the concurrent flows (more if possible);
- → **install fishways in various areas likely to be visited** by shad. For hydroelectric developments bypassing sections of watercourses, the installation of two fishways, one at the dam and another at the plant should be assessed, as long as the station is not overdesign compared to flows met during migration;
- → **multiply the number of entrances while making sure they are located in calm areas** from a hydraulic point of view to ensure attraction. The installation of several entrances must be assessed when the structures' width is more than 20 m. For structures with a width of more than 100 metres, it is necessary, in most cases, to install several entrances or fishways;
- → **for hydroelectric stations, implement rules on the prioritisation of units in operation** in order to attract fish near the entrances (without reducing the attraction);
- → **ensure good attraction of entrances up to flows of about twice the mean annual discharge** of watercourses, while maintaining falls of 0.20 to 0.25 m;
- → **have large sized entrances** given that the species moves in schools. A minimum width and depth of 2 m and 1.5 m, respectively, can be considered which corresponds to flows per entrance of 5 to 6 m^3/s. Make sure that watercourses of modest size have entrances of a minimum width and depth of 1 m and 0.7-0.8 m, respectively, i.e., a minimum flow of about 1.5 m^3/s.

Conditions favourable for an easy and quick migration of shad must be ensured once fish are inside the fishways. The following criteria are particularly important: selection of the type of fishway, internal hydraulic conditions and the size of the structures (considering the fact that shad move in schools).

The baffle fishway and locks that are not free surface flow (Borland-type, for example) are not recommended for shad: the baffle fishway possess unfavourable internal hydraulic conditions (helicoidal flows, highly-aerated water) and the Borland locks are not well-suited to shad behaviour.

Fishways that consist in dividing the total fall into several smaller falls (fish ladders, pre-dam, etc.) by the installation of successive basins are suitable for shad. Several recommendations must be taken into account:

- → **passage areas must be free flowing (deep notches to be prohibited) and must be located near the banks;**
- → **falls must have streaming flow** with height between 0.20 and 0.25 m;
- → **energy dissipated in the basins must be less than 150 W/m^3**. For pre-dam, higher values can be acceptable in the event for example where the number of basins to pass through is generally limited;
- → **fish migration should be available on all water column depth.** This requires the implementation of deep passage areas. For example, when using fish ladders, vertical slot fishways must be favoured;
- → **volume of water in basins must befit the requirements of the species**. Minimum volume of about 10 to 15 L per shad can be considered. Size of structures must be suitable to the size of migration runs. For fish ladders, minimum volumes of 12 m^3 per basins can be considered, for example, so as to ensure satisfactory migration conditions of 100,000 fish per year.

Lifts, whose installation must be considered when fall heights exceed 8 to 10 m, can also be suitable for shad migration. However, it is important to make sure **water volumes in holding tanks and lifting tanks correspond to at least 30 L and 10-15 L per fish**, respectively. Their dimensions must be adapted to the size of migration runs. The following can be noted: the maximum daily migration can correspond to approximately 10% of the annual migration and the hourly migration peak can represent 15% of the maximum daily migration. It is also important to limit risks of fish exiting once they entered the crowder. The **upstream migration cycle must be short, about 15 min during the main migration period**, but less than 30 min at all times. Passage areas near the non-return device must present characteristics that limit reluctance of fish to enter the fishway, but that prevent their rapid exit. We recommend having **passage areas 0.3 to 0.4 m wide and establishing a very gradual narrowing towards the upstream of the crowder.**

For fish ladders and lifts, special attention must be paid to:

- → **injection of attraction flows**. It is recommended to divide flows in several points of the fishway so as to favour attraction of upstream flow;
- → **no marked change in direction** likely to affect fish movements;
- → **connections of the various entrances** (to the downstream collecting tunnels or connection of separate entrances to one fishway) where fish progression can be disrupted and cause them to exit. It is recommended to limit the number of entrances (3 to 4) connected to one tunnel or one fishway and to make sure there is no marked change in direction. The installation of deflectors or guiding walls (which direct flows and guide fish) must be systematically assessed.

Navigation locks can be efficient in certain situations as long as they are properly positioned so that their operation is adapted for fish, that they have access to significant flows compared to concurrent flows and that constraints caused by fluvial navigation allow for sufficient number of cycles. Problems related to parking and exit of fish sometimes appeared during the attraction phase. These problems can be mitigated by optimising the position of the downstream gates (reduction of the passage width, closing of gate as to make a “chicane”) and/or by reducing the duration of cycles.

Even if there is no detailed information on the shad migration through “natural” fishways, such as ramps with evenly placed blocks, and successive weir ramps, there is no reason to doubt that they comply with shad requirements. That is if slopes are modest (maximum of about 5% for blocks ramps and maximum of 6% for successive weir ramps), there is adequate draft (minimum of 0.4 m) and stream surface falls for the successive weirs. The advantage of these fishways is that they are less likely to be blocked by floating debris.

There is no detailed information on shad migration in bypass rivers. These fishways often have very high efficiencies for certain species, such as big anadromous salmonid, and seem suitable for shad. However, it is important to make sure entrances are properly positioned, possess sufficient attraction, and that the internal hydraulic conditions are appropriate (no unfavourable falls or areas where velocity is greater than the fish’s capacity, sufficient flow depths, rest areas for fish when the length of the fishway is significant). Mean slopes of 1% to 3%, combined with devices that help dissipate energy, such as groynes, evenly placed roughened blocks or low-rise weirs with basins, must allow high migration.

In the end, improvement of the shad’s migration must take into account all issues they are faced with. It often requires the implementation of multiple migration paths and substantial flows. The fishways to be installed often have high construction costs, especially on large watercourses, and can lead to sometimes significant production losses for hydroelectric stations. It seems impossible to guarantee efficiencies of 70-75% even when complying with the recommendations established in this report, especially for sites of significant size.

Considering these conditions, the cumulated impacts of a couple of structures on one migratory axis quickly become very significant and can sometimes make the management and restoration of species difficult, especially when the structures are located in the low sections of basins, downstream from the best areas for reproduction and growth of juveniles.

It seems necessary to have further feedback on the behaviour of shad near and inside the fishways, especially feedback that are based on or close to the recommendations of this report.

In France, interesting information could be extracted from the fish ladders with multiple entrances built at major hydroelectric stations on the Rhine, Rhône, Dordogne and Garonne.

It seems necessary to monitor “natural” fishways, especially the ramps with evenly placed blocks, which are said to be efficient for shad, but for which we do not have precise information (Gave d’Oloron, Charente, Vienne, Gardon, etc.).

It would be useful to optimise the crowder of lifts (funnel angle, V configuration or baffle, etc.).

In the United States, improvements that will be made so as to optimise migration and related studies for any relicensing must be monitored (including Holyoke and Turners Falls on the Connecticut, Lowell on the Merrimack, and Conowingo, Holtwood and York Haven on the Susquehanna).

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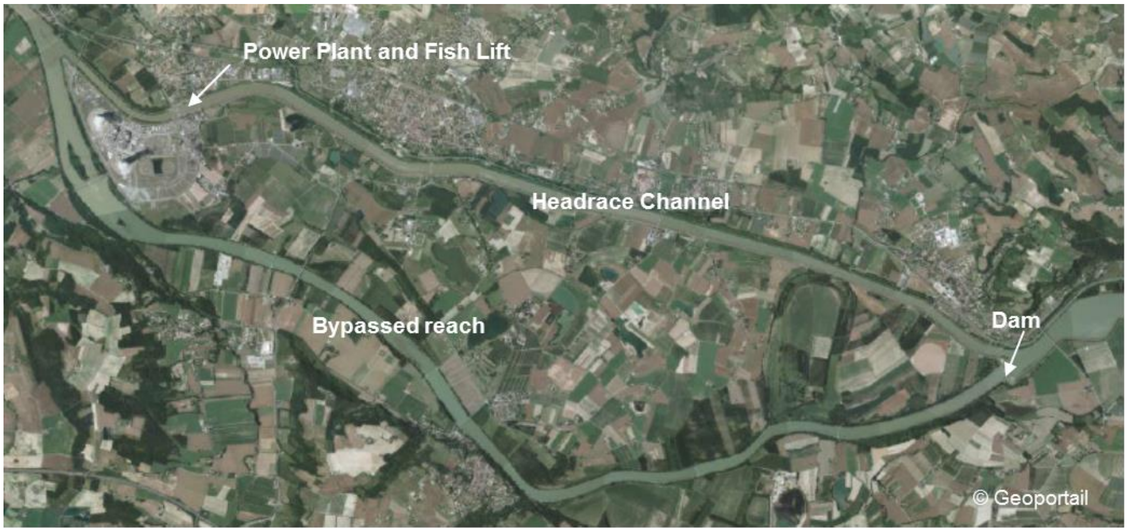
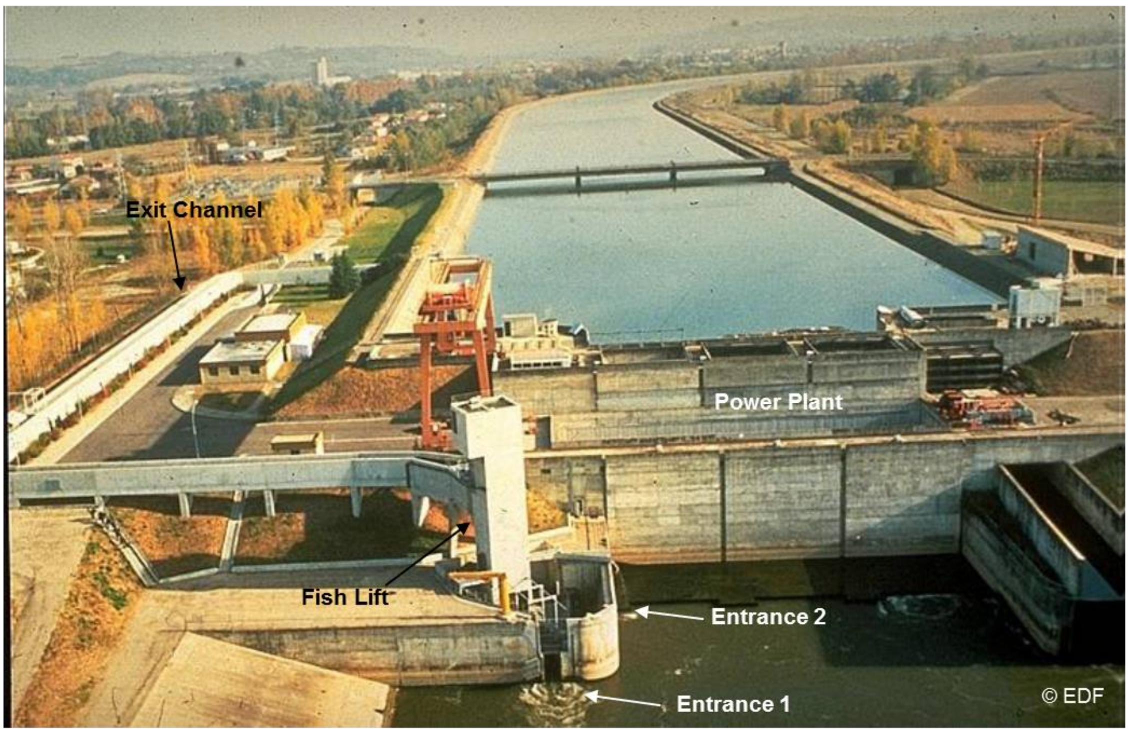
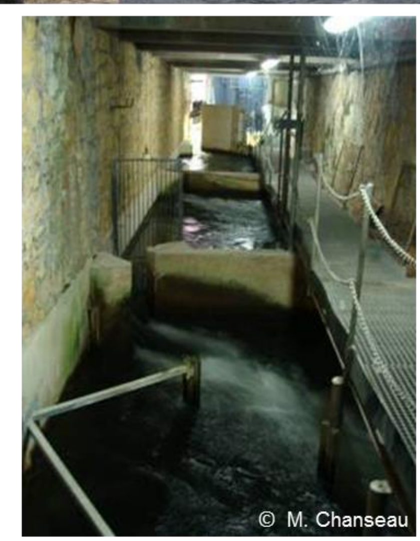
Pictures



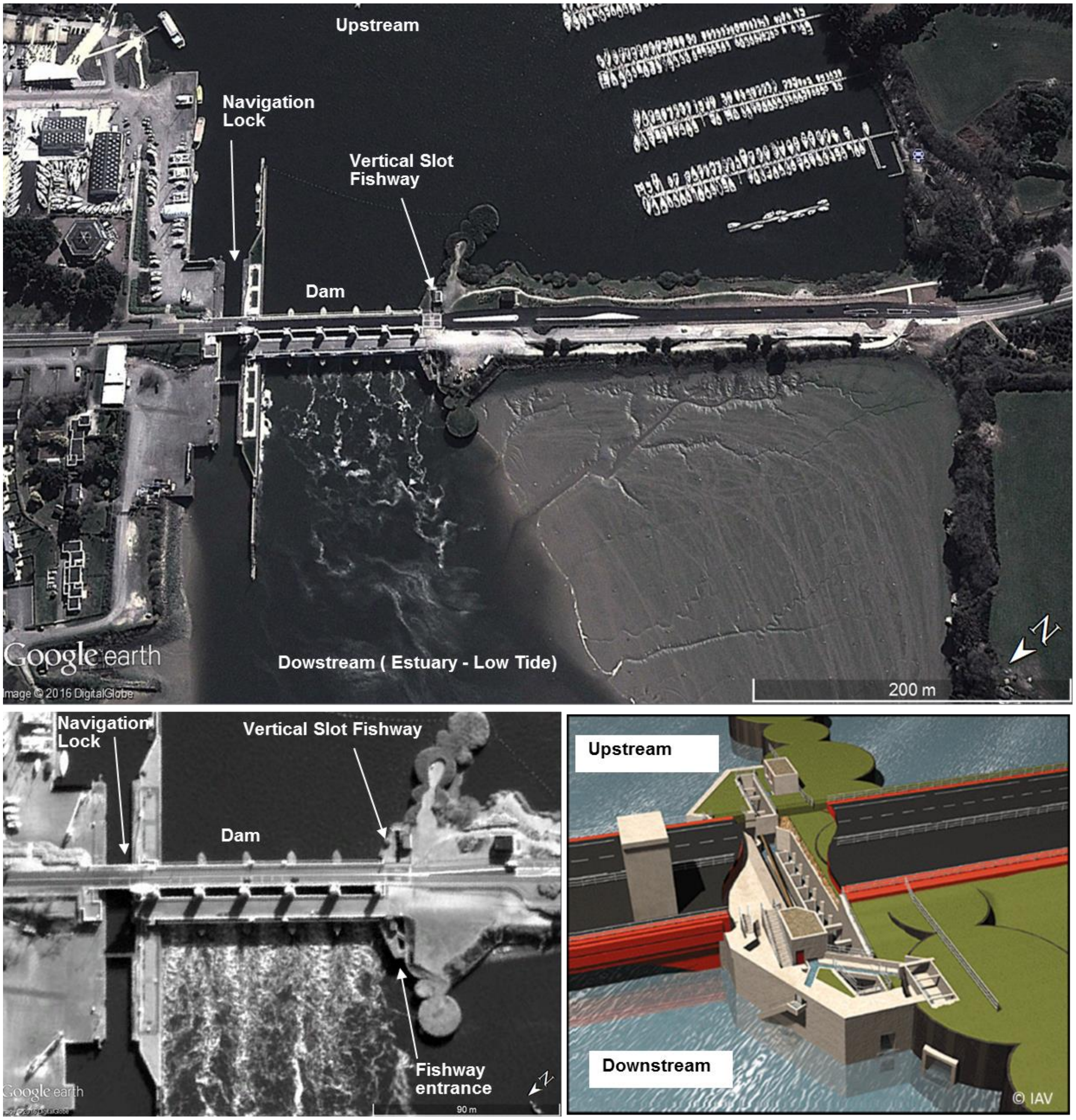


FRANCE 1: GARONNE – GOLFECH: (top to bottom, left to right): aerial view of the Golfech development on the Garonne; aerial view of the power plant, of the fish lift and the two entrances; view of the connecting channel between entrances 1 and 2 and the fish lift; view of the fish crowder.

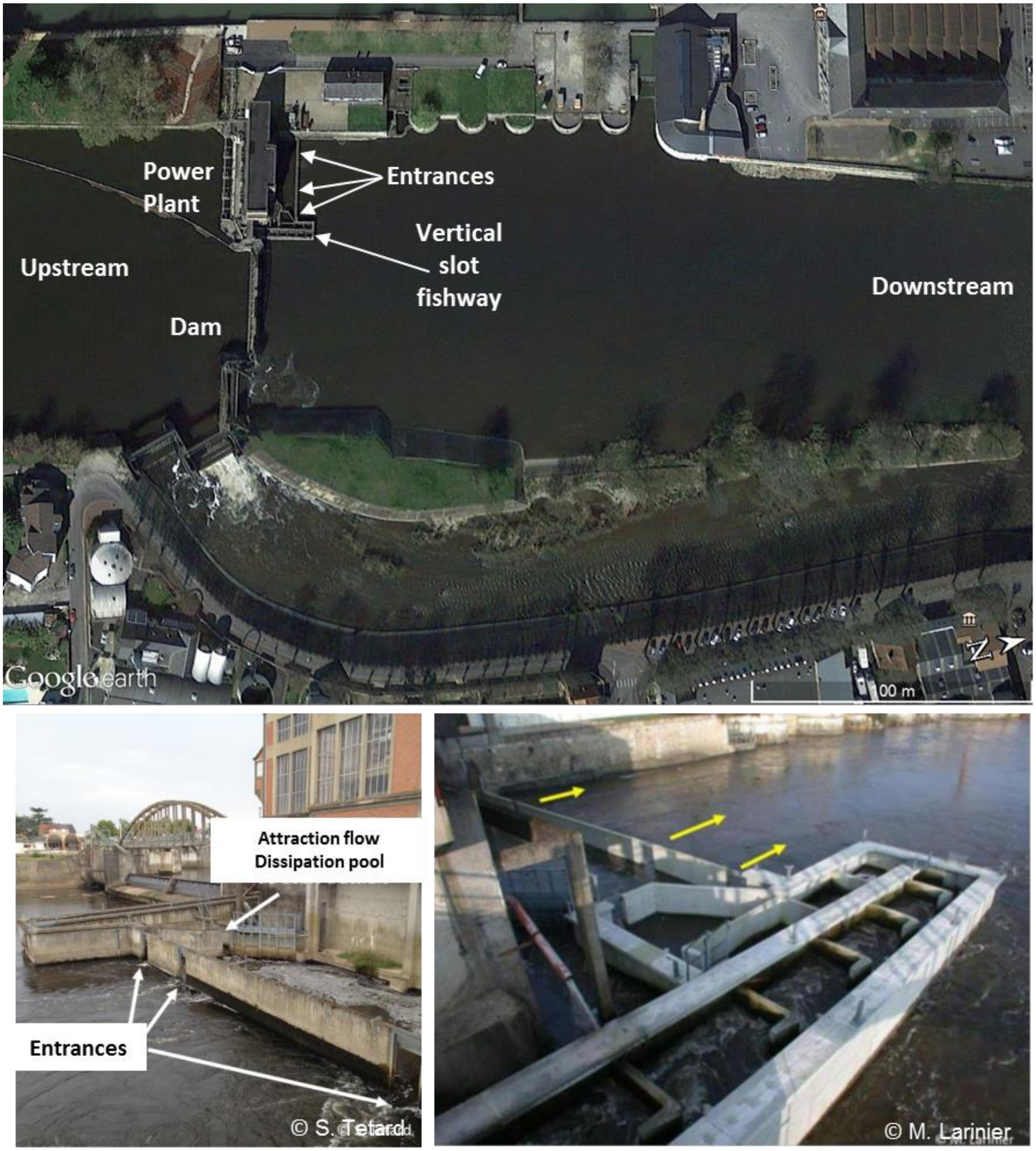


FRANCE 2: DORDOGNE – TUILIERES: (top to bottom, left to right): aerial view of the Tuilières site on the Dordogne River; downstream view of the power plant, the fish lift and spillway; view of the fish lift; view of lift's holding pool and fish crowder; view of fish ladder in which fish are released.

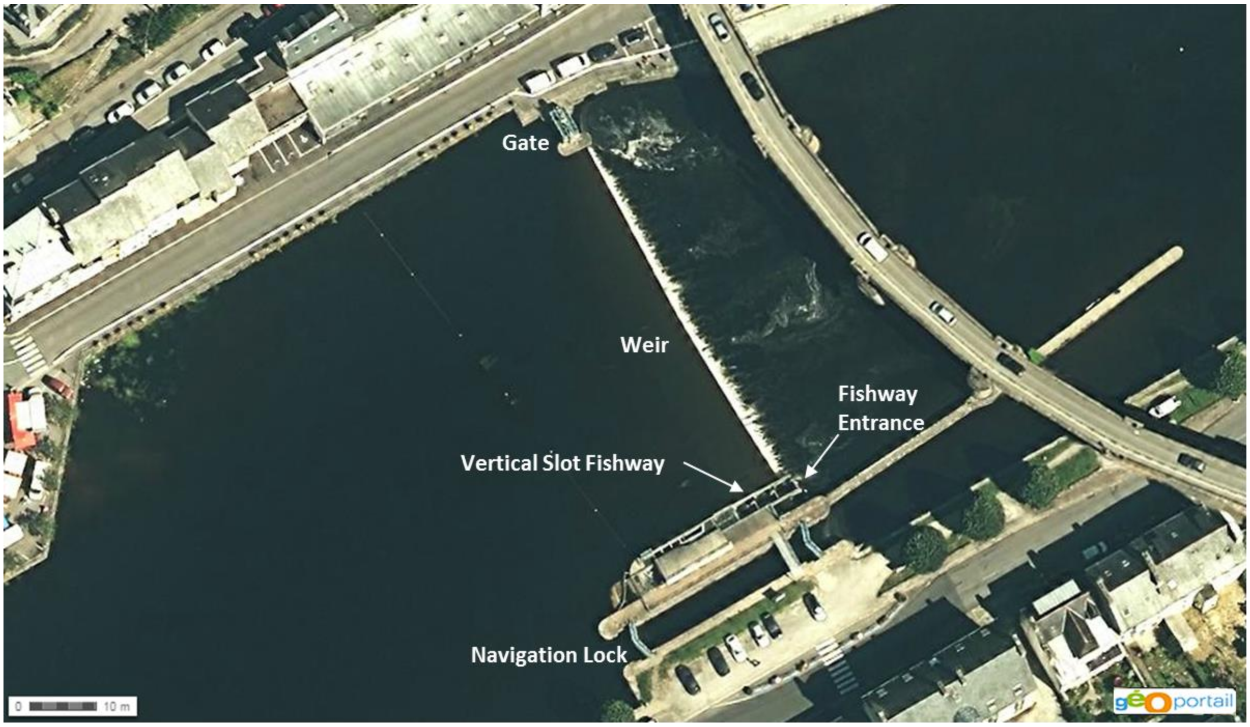
FRANCE 3: ALLIER – VICHY: (top to bottom, left to right): aerial view of Vichy site on the Allier River; view of Vichy dam and vertical slot fishway.

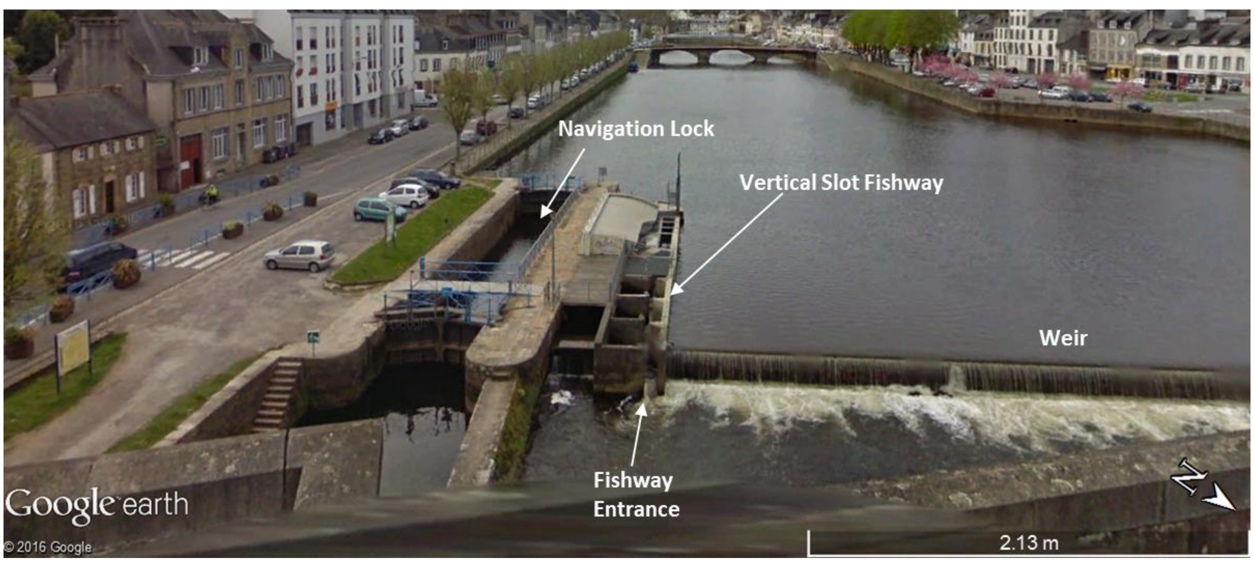


FRANCE 4: VILAINE – ARZAL: (top to bottom): aerial view of Arzal dam on the Vilaine River and 3D representation of the vertical slot fishway.

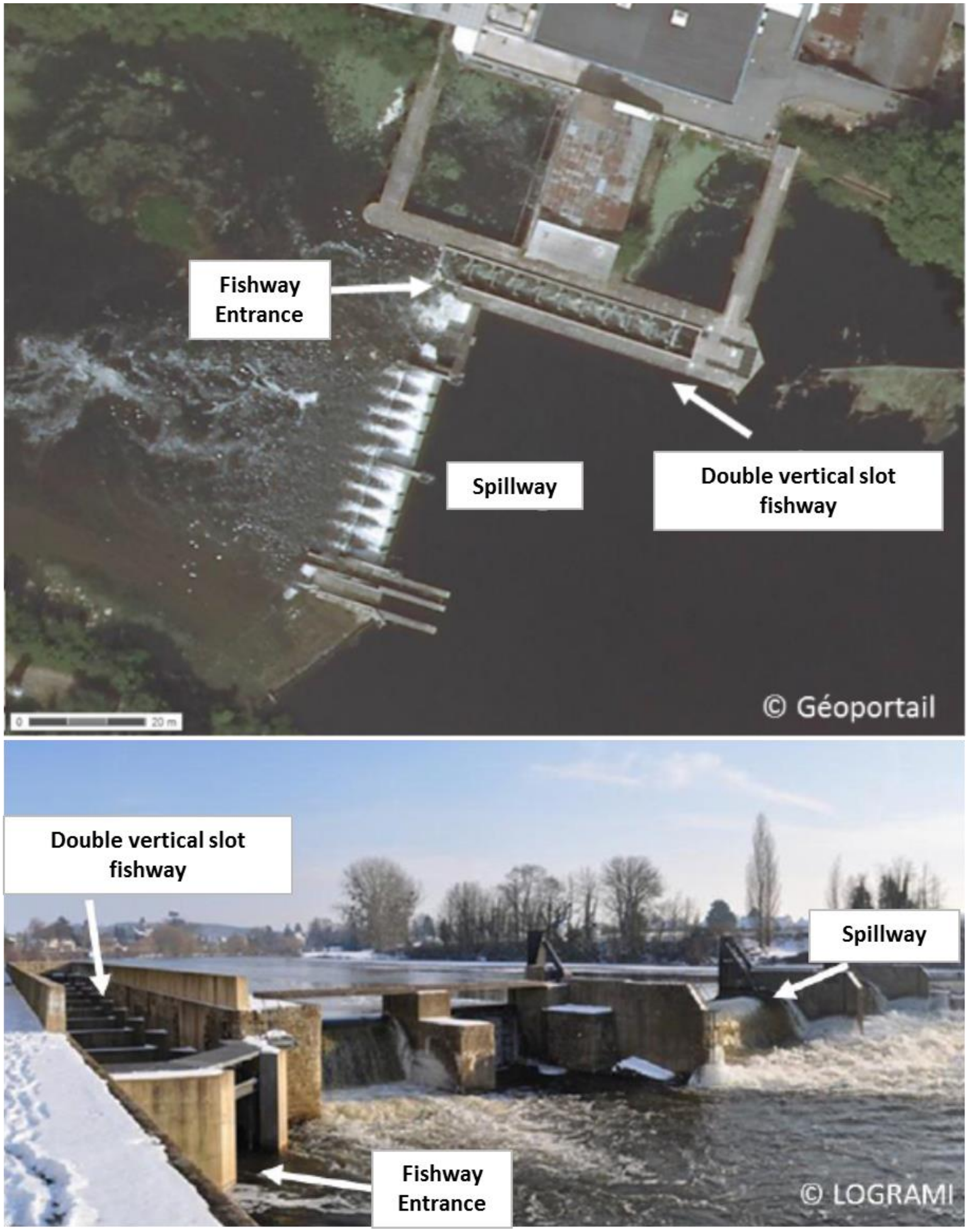


FRANCE 5: VIENNE – CHÂTELLERAULT: (top to bottom, left to right): aerial view of Châtellerault site on the Vienne River, of the vertical slot fishway and the three entrances.

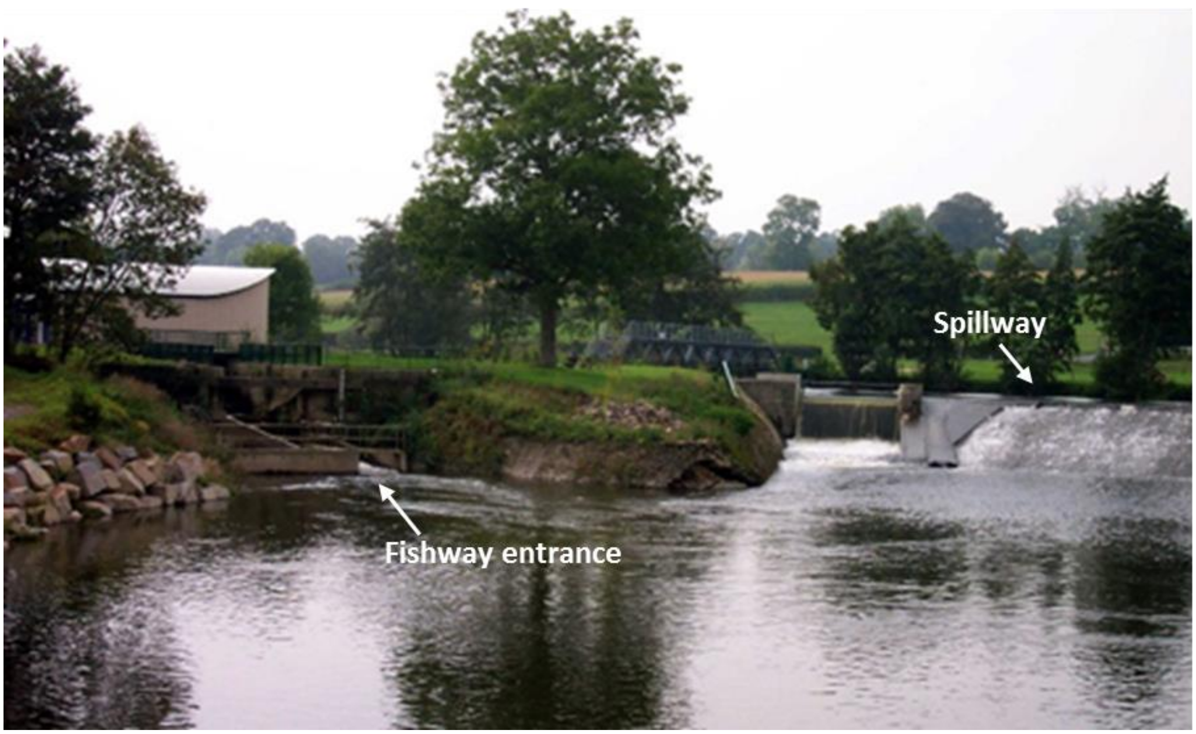




FRANCE 6: AULNE – CHÂTEAULIN: (top to bottom): aerial view of Châteaulin site on the Aulne River, and of the vertical slot fishway.

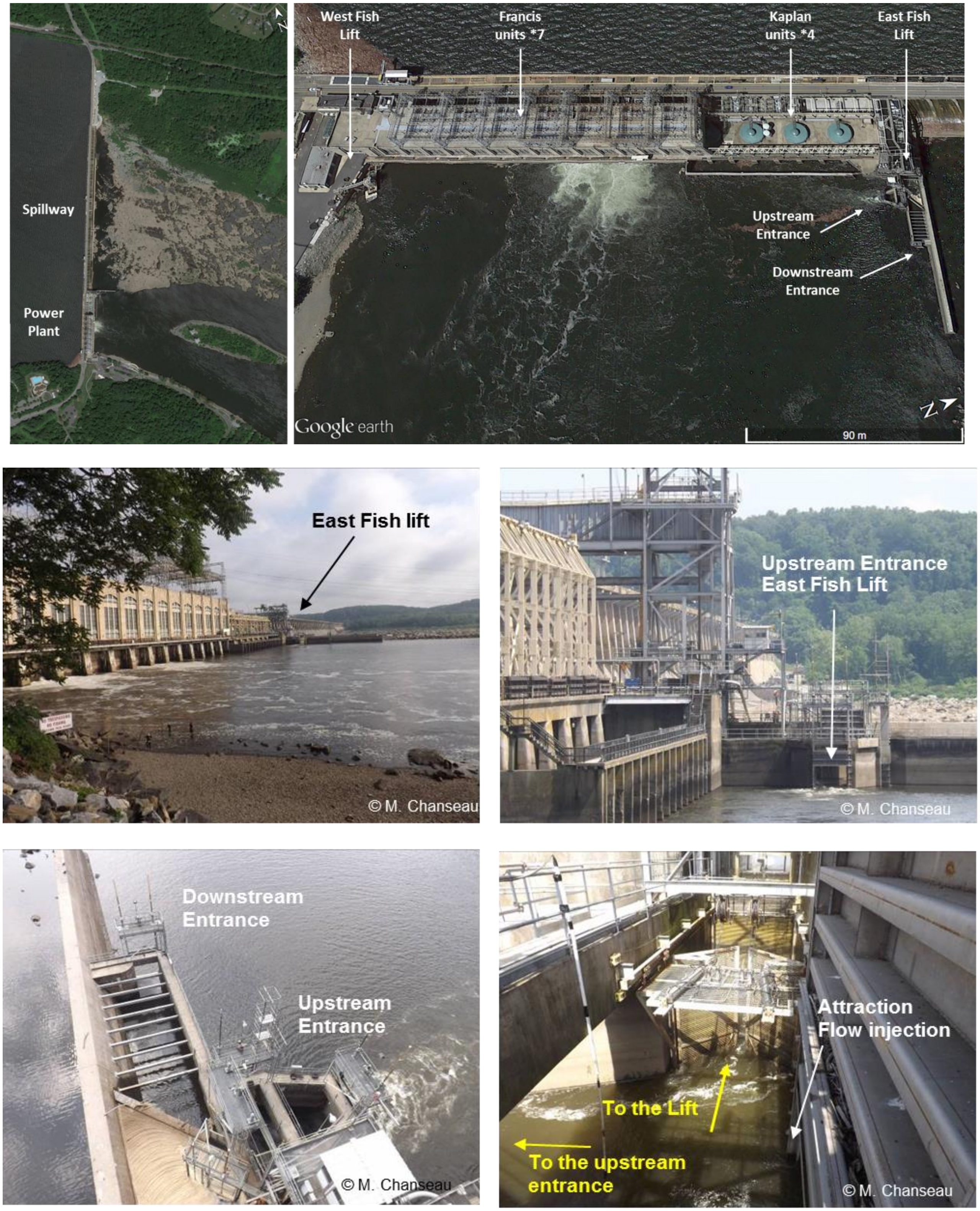


FRANCE 7: CREUSE – DESCARTES: (top to bottom): aerial view of Descartes site on the Creuse River, and of the double vertical slot fishway entrance.

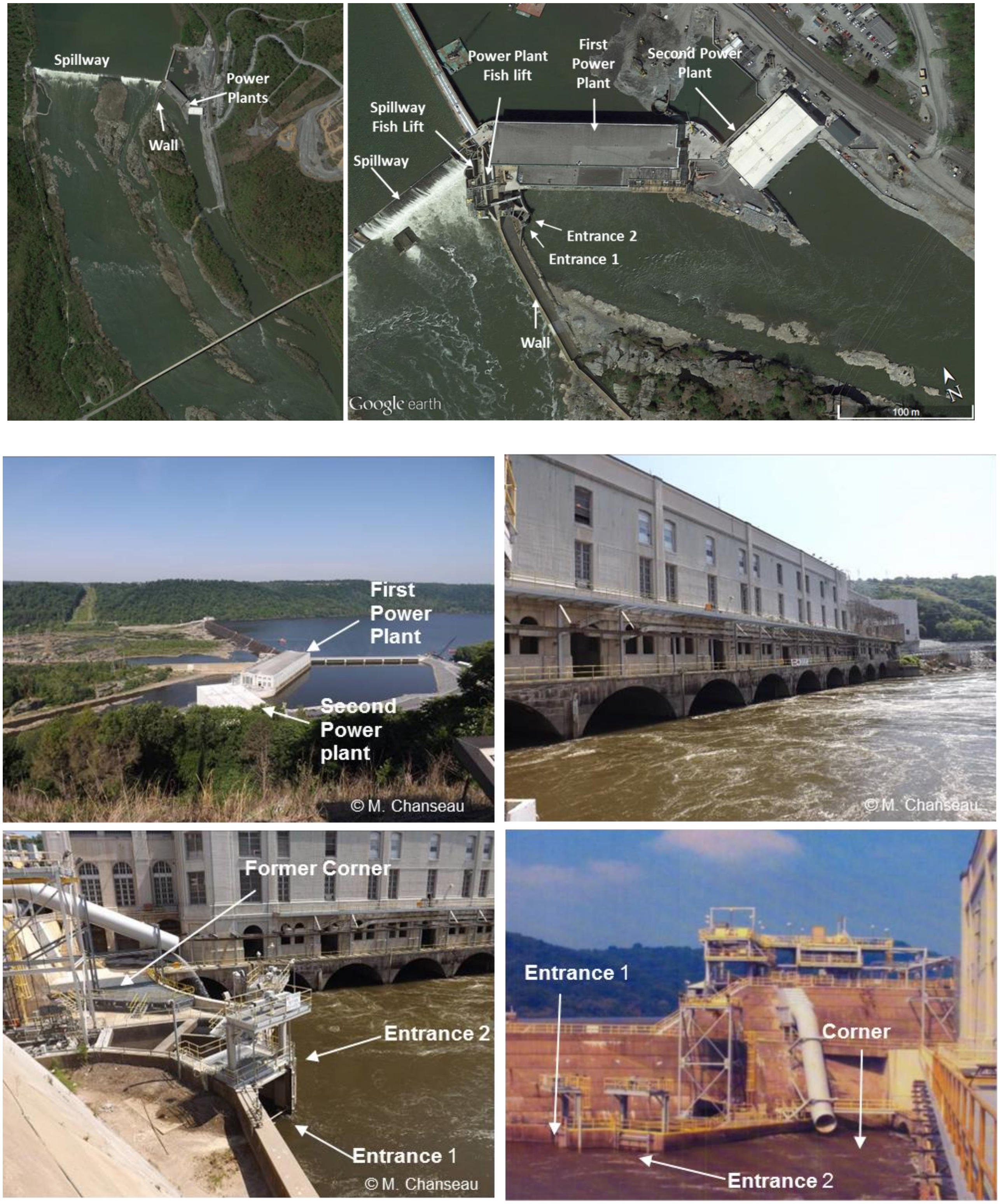


FRANCE 8: VIRE – CLAIES DE VIRE: (top to bottom): aerial view of the Claies de Vire site on the Vire River, and of the vertical slot fishway entrance.

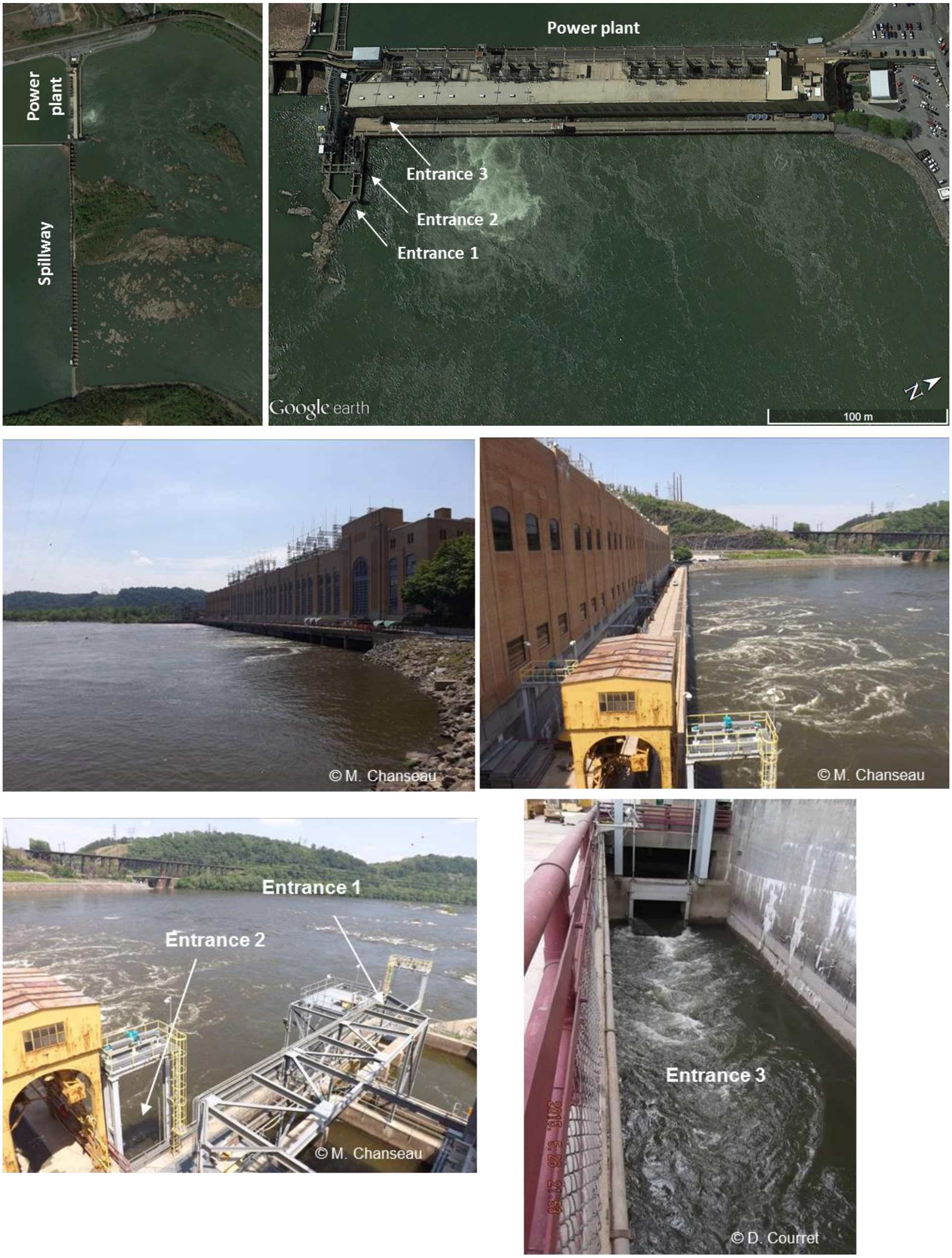
FRANCE 9: ORNE – MAY SUR ORNE: (top to bottom, left to right): aerial view of the May sur Orne site on the Orne River; view of the weir upstream section; view of the fishway entrance; view of the vertical slot fishway



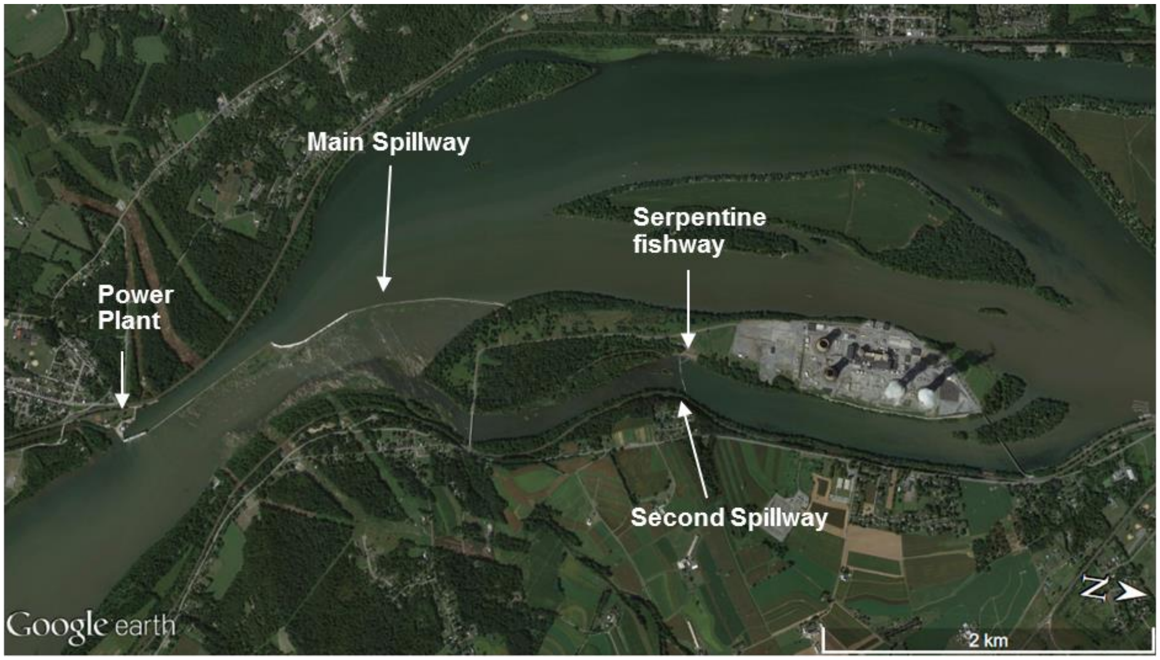
UNITED STATES 1: SUSQUEHANNA – CONOWINGO : (top to bottom, left to right): aerial view of the Conowingo site on the Susquehanna River; downstream view of the power plant; view of the East fish lift; view of the two entrances of the East lift; view of the attraction flow injection area (East lift).



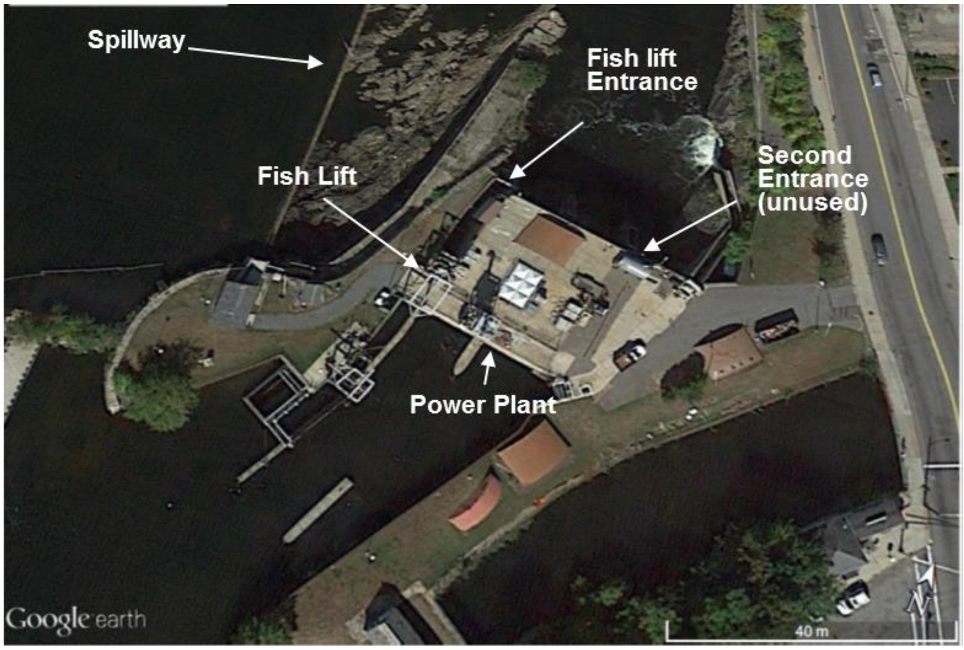
UNITED STATES 2: SUSQUEHANNA – HOLTWOOD: (top to bottom, left to right): aerial view of the Holtwood site on the Susquehanna River; aerial view of the site; view of the two power plants and of the spillway; downstream view of the first power plant; view of the two entrances of the power plant fish lift; view of the corner, sealed in 2010 (see previous picture) (Tryninewski, et al., 2012).



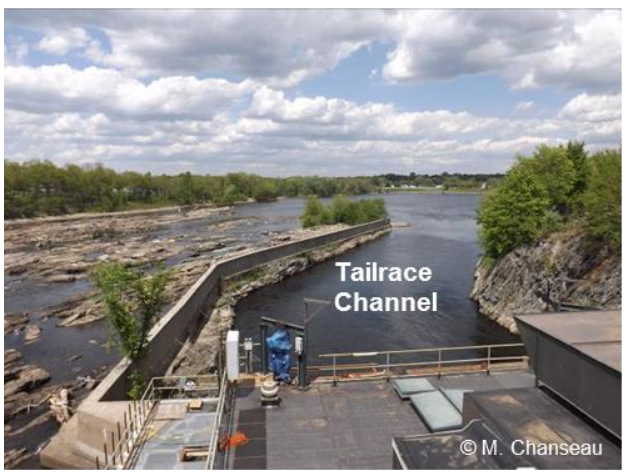
UNITED STATES 3: SUSQUEHANNA – SAFE-HARBOR: (top to bottom, left to right): aerial view of the Safe Harbour site on the Susquehanna River and of the three entrances of the lift; view of the power plant from the left bank; view of the power plant from the right bank; view of Entrances 1 and 2 (unused); view of Entrance 3.



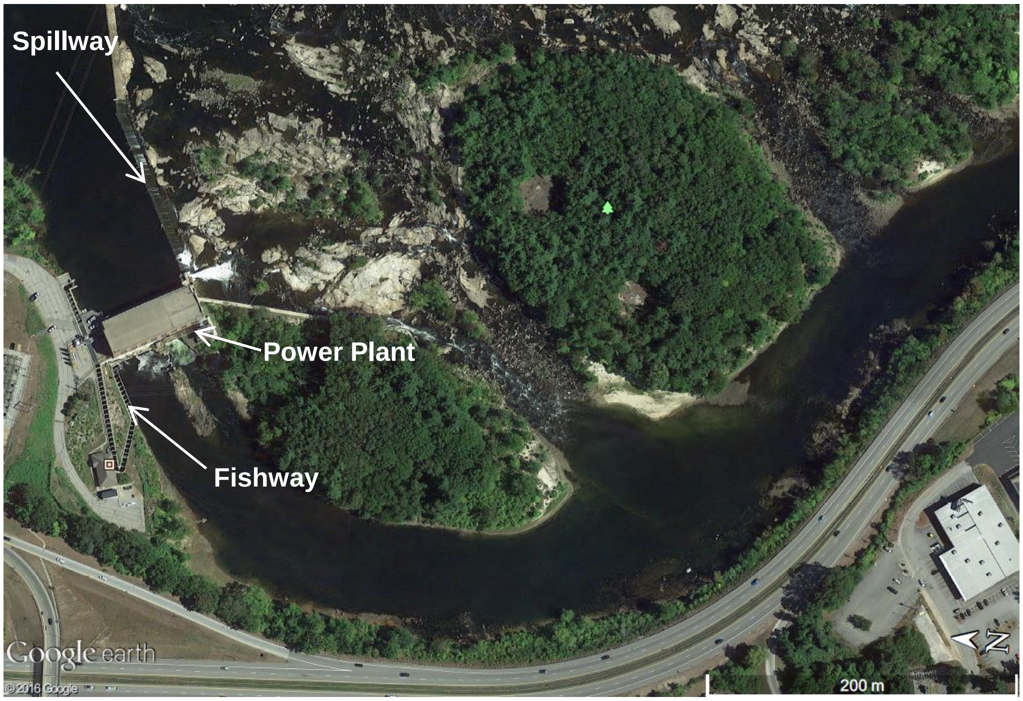
UNITED STATES 4: SUSQUEHANNA – YORK-HAVEN: (top to bottom, left to right): aerial view of York Haven site on the Susquehanna River; aerial view of the fishway; view of the fishway entrance and of the attraction flow; view of the downstream section of the fishway (slots); view of the upstream section of the fishway (serpentine).

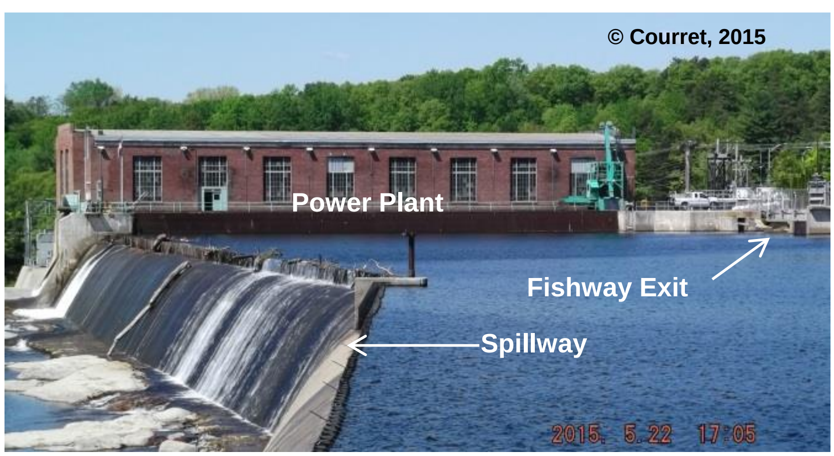


UNITED STATES 5: MERRIMACK – LAWRENCE: (top to bottom, left to right): aerial view of the Lawrence site on the Merrimack River; view of the tailrace channel; downstream view of the power plant and of the two entrances; view of the fish lift entrance; view of the fish crowder.



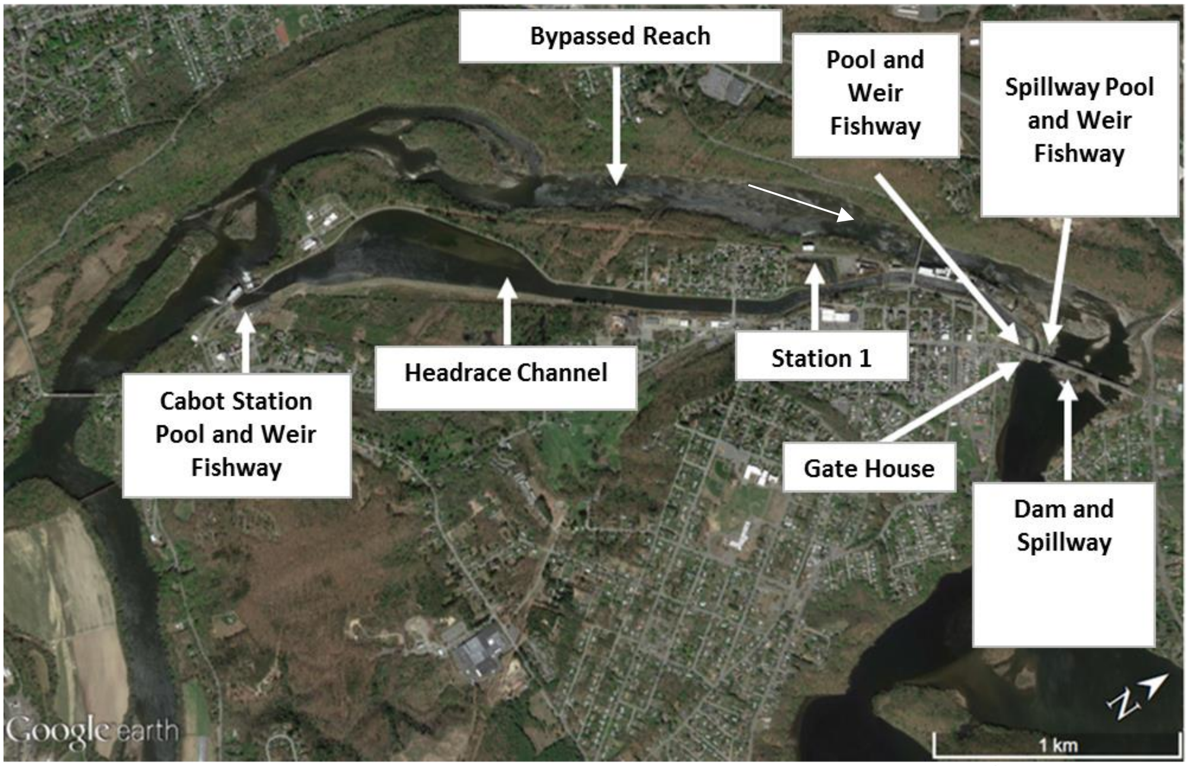
UNITED STATES 6: MERRIMACK – LOWELL: (top to bottom, left to right): aerial view of the Lowell site on the Merrimack River; tailrace channel; downstream view of the power plant and the fish lift entrance; view of the fish entrance and of the deflector; view of the fish crowder.

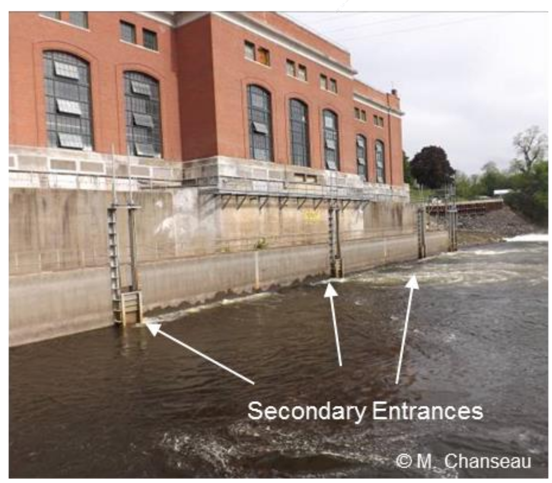




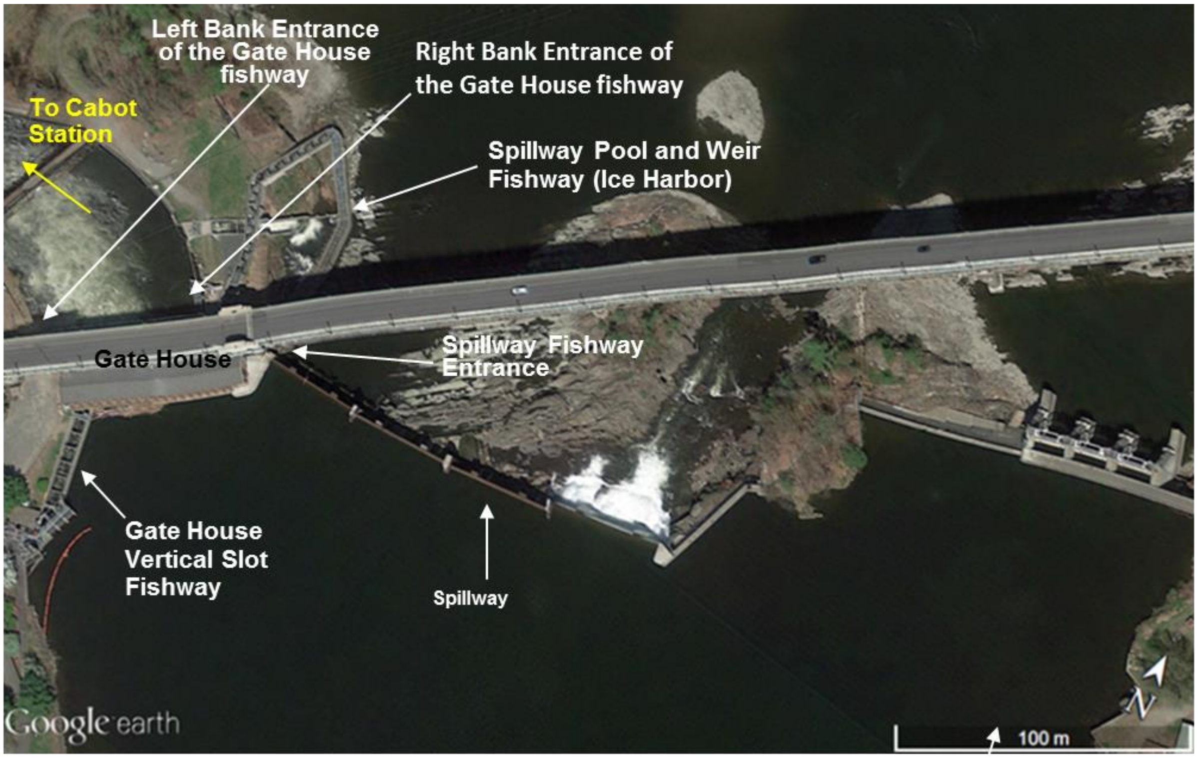
UNITED STATES 7: MERRIMACK – AMOSKEAG: (top to bottom, left to right): aerial view of the Amoskeag site on the Merrimack River; view of the tailrace channel and the fishway entrance; view of the fishway exit.

UNITED STATES 8: CONNECTICUT – HOLYOKE: (top to bottom, left to right): aerial view of the Holyoke site on the Connecticut River ; downstream view of the power plant; view of the two entrances of the fish lift at the plant and the collecting channel; view of the fish crowder (Power Plant Fish Lift); view of the lift entrance (Spillway Fish Lift).

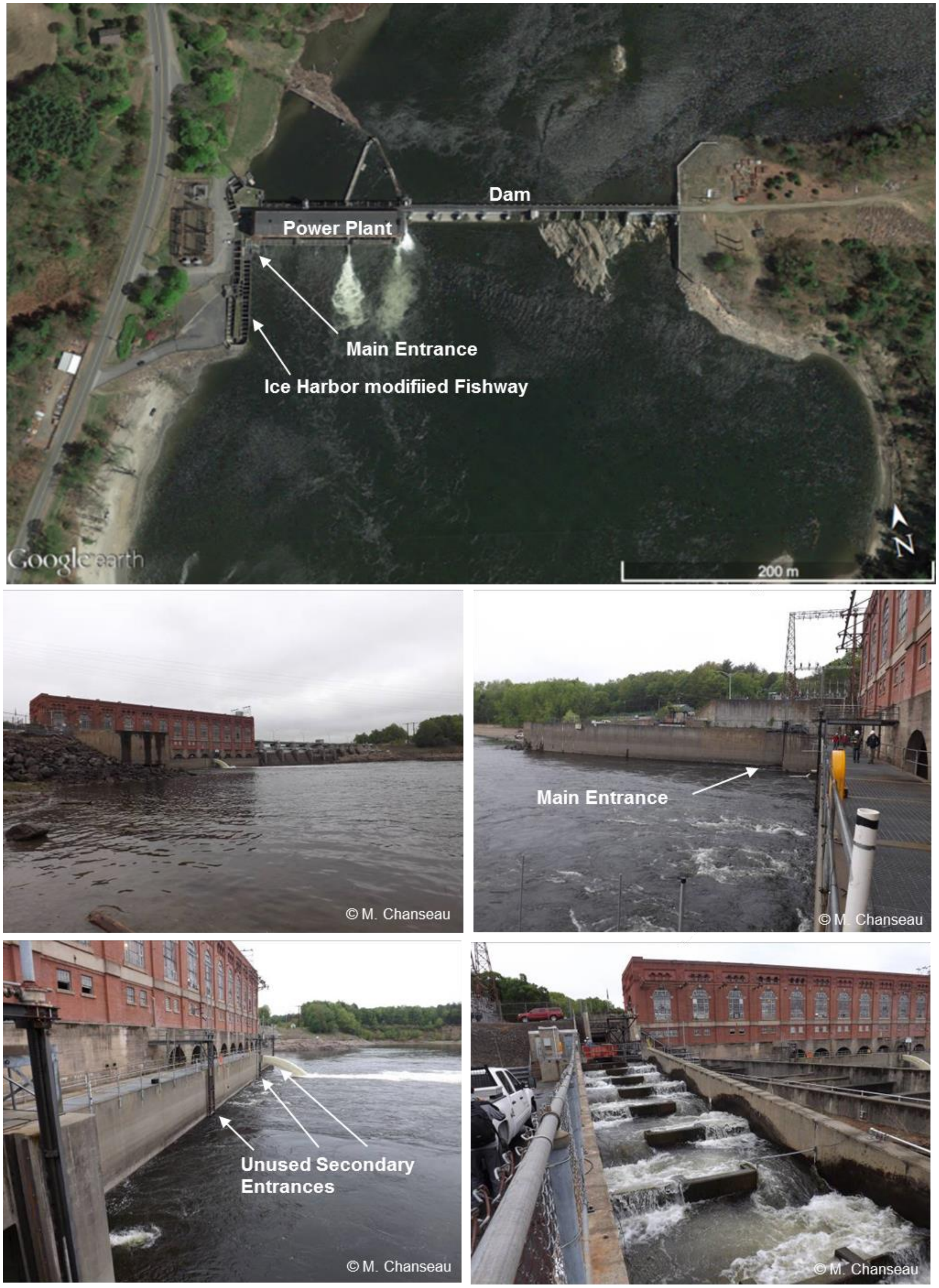




UNITED STATES 9: CONNECTICUT – TURNERS-FALLS: (top to bottom, left to right): aerial view of Turners Falls site on the Connecticut River; aerial view of the Cabot station; view of the fishway at Cabot station; view of a drop between two pools at Cabot station; downstream view of the Cabot station and of the various entrances (unused) connected to the collecting channel.



UNITED STATES 9: CONNECTICUT – TURNERS-FALLS (cont'd): (top to bottom, left to right): aerial view of the Gate House and dam; view of the Gate House vertical slot fishway; view from downstream of the Gate House and the two entrances; view from upstream of the two entrances of the Gate House fishway; view of the Spillway Ice Harbor fishway.



UNITED STATES 10: CONNECTICUT – VERNON: (top to bottom, left to right): aerial view of the Vernon site on the Connecticut River; downstream view of the plant; view of the fishway entrance; view of the unused secondary entrances; view of the Ice Harbor fishway.