

FINAL REPORT

O17 Investigation of Factors Affecting Fish Passage in Culverts (2019/20)

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SUMMARY

Currently in Queensland, waterway barrier works approvals are triggered by constructing or raising a waterway barrier, which includes new or modified culverts, causeways, some bridges and flood ways due to the associated physical barriers to fish passage including increased water flow velocities. Fish passage requirements for culverts where waterway barrier works are required are prescriptively defined by the Queensland Department of Agriculture and Fisheries (DAF) including a requirement for full-height rectangular baffles. Where designs do not comply with the prescriptive designs the applicant must prove that the design is suitable for fish passage, and the current body of knowledge available on what is 'suitable for fish passage' is limited.

This report contains a review of the literature relating to fish characteristics relevant to fish passage and potential constraints to fish passage posed by culverts. Fish species found in Queensland have been the primary focus but some limited review of interstate and overseas literature relating to fish passage practice has been included.

A range of factors relating to fish migration have been explored, including migration patterns, seasonality, regionality and triggers for migration. The current body of knowledge on fish swimming ability has been reviewed, along with specific behaviours which may contribute to passage success such as station holding. Possible constraints to fish passage posed by culverts have been explored, including excessive velocities, turbulence, water depth, light contrasts and water temperature. A review of fish passage guidelines interstate and in New Zealand has been completed with the aim of identifying best practice approaches to fish passage legislation, design and remediation.

Knowledge gaps relating to each of the topics reviewed are presented together with recommendations for potential further work. A selection of key findings from the review of literature include:

- Migration in response to increased flow is common for both diadromous (move between saltwater and freshwater) and potamodromous (freshwater only) fishes. This is often linked to wet season rains in Queensland. The flows that fish move during varies depending on species and life stage.
- Different flow regimes in coastal and inland (of the Great Dividing Range) catchments mean that fish may need to migrate during higher discharge conditions in western systems compared to eastern systems. Due to differing fluvial geomorphologies, this may not equate to higher stream velocities.
- Laboratory investigation of 21 small-bodied NSW/QLD fish species swimming ability has shown that a 0.3 m/s maximum velocity guideline is well supported for a culvert length of 8 m. Three out of four species which could not gain passage at this velocity may otherwise be able to gain passage through specialised behaviours such as station holding (Watson et al. 2019).
- Approaches to fish passage guidelines in other states are generally less prescriptive than Queensland. The Victorian guidelines recommend an approach where performance objectives for a structure are developed on a case-by-case basis, but there are general hydraulic criteria provided.

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1 INTRODUCTION

1.1 BACKGROUND

The *Fisheries Act* 1992 stipulates that works or structures that restrict the movement of fish stock along a waterway require an approval for 'waterway barrier works'. A waterway barrier works approval is triggered by constructing or raising a waterway barrier and covers new or modified culverts, causeways, some bridges and flood ways due to the associated physical barriers to fish passage including increased water flow velocities.

Currently for culverts where waterway barrier works are triggered, fish passage requirements are prescriptively defined in the 'Accepted Development Requirements' (Queensland Department of Agriculture and Fisheries 2018). This involves the requirement for full-height rectangular baffles for high or major risk waterways. Where designs do not comply with the Department of Agriculture and Fisheries (DAF) prescriptive designs, the onus is on the applicant to provide evidence that the proposed design will be suitable for fish passage. At present, the body of knowledge available on what is 'suitable for fish passage' is limited.

The current practice of reliance on the existing prescribed designs which have not been robustly tested has led to sub-optimal outcomes from an engineering and hydraulic perspective. TMR has concerns that the prescriptive design-solutions may be limiting effectiveness for fish passage, cost-effectiveness of construction and practicality of this approach for the full range of potential situations. There are a range of alternative design solutions available, but without scientific evidence of suitability, DAF may not have confidence that proposed designs will be effective for fish passage and are unlikely to approve them.

The Queensland Department of Transport and Main Roads (TMR) seeks to expand and encourage the development of innovative solutions for fish passage through:

1. defining the functional requirements required for effective fish passage through culverts (focusing on relevant Queensland species)
2. based on (1) develop functional hydraulic requirements for structures requiring fish passage
3. based on (2), develop functional structural and constructability requirements for the various physical culvert configurations.

In building this body of knowledge, the intent is to collaborate with DAF to develop a greater range of suitable options for structures where fish passage requirements are applicable.

Definition of these requirements would assist with both the design of new and modified culverts and will facilitate the effective migration of Queensland fish species populations in future. Year 1 of this project will progress the definition of the functional requirements for effective fish passage through culverts. Following on from this work, Year 2 of this project will focus on progressing the development of functional hydraulic requirements for box culverts. The outcomes of the Year 2 project work will be discussed in a future report.

1.2 AIMS & OBJECTIVES

The aim of this project is to investigate fish behavioural characteristics relevant to fish passage in Queensland and define the related functional requirements for fish passage through culverts. This is achieved through the following objectives:

1. Conduct a literature review of existing material relating to fish characteristics relevant to fish passage and potential constraints to fish passage posed by culverts with a focus on species of fish found in Queensland.
2. Through (1), identify knowledge gaps and requirements for further research relating to relevant fish characteristics and constraints.

1.3 SCOPE

The literature review is focused on research related to Queensland fish species. Research conducted in other states or overseas is consulted with the intention of identifying potential further research to be conducted for Queensland fish species.

The review considers fish passage through culverts only. Other structure types are not considered in detail. The review is focused on the requirements of fish and potential barriers to their passage, and while possible treatments are partially considered in this context, this review is not intended to comprehensively investigate potential treatment/remediation options for culverts.

2 LITERATURE REVIEW

2.1 BACKGROUND

There are at least 300 freshwater fish species found in Australia, with approximately 145 of these found in Queensland (Queensland Department of Agriculture, Fisheries and Forestry 2014). There may be considerable diversity within each individual catchment, with at least 56 species found in the Tully-Murray catchment as an example (Kapitzke 2010b). The level of diversity is common in the wet tropics region of Queensland (Kapitzke 2006), but diversity is likely to be lower in other regions. In particular, 13 species were found through sampling in the Barcoo River (Kerezszy, Arthington & Balcombe 2014). Generally, perennial waterways will support a higher level of species diversity compared to ephemeral waterways (Kapitzke 2010b).

The swimming ability and migratory behaviour of fish found in each catchment may vary considerably, often having been developed in response to the requirements of their typical habitat (Wang & Chanson 2017). The fish present in each region and even in individual waterways in a specific region may vary greatly in terms of behaviour and swimming ability. Streams may act as a pathway between different fish habitats, and fish habitat conditions may vary across the cross-section of a typical stream.

Since fish have developed to take advantage of the natural conditions within the habitats that they inhabit, the installation of in-stream structures including culverts which alter the natural flow conditions may impact on the ability of fish to migrate upstream when needed. There are several key constraints to fish passage which may be generated by culvert installations, including excessive velocities, turbulence, shallow water depths, darkened conditions within the culvert, and vertical barriers (Kapitzke 2010b). Since around the turn of the century in Australia, there has been an increasing focus on installing new culverts which minimise impacts on migrating fishes and remediating existing structures to ameliorate barrier effects.

When remediating a site to provide fish passage, the ideal solution from the perspective of fish passage is the removal of the culvert and restoration of the stream back to original conditions. It is recognised that this may not be viable in the majority of situations, where the existing culvert provides an important waterway crossing. Often the next most desirable option is the removal of the existing culvert and the installation of a bridge which minimises streamflow disruption. In the case of bridge installation, the most desirable option is a single span bridge which does not include piles driven into the riverbed as this minimises impact on streamflow (Franklin et al. 2018; Hyde 2007). Bridge installations are often not economically viable, especially in situations where site conditions are limiting. This necessitates the development and provision of effective fish passage designs and remediation options for culverts that produce conditions which are as close to natural stream conditions as possible during flows when fish are attempting passage.

In order to promote biodiversity as much as possible, it is desirable for designs to be controlled by the swimming ability of the weakest fish species expected to require passage (Franklin et al. 2018). It may not be feasible to provide passage to every individual fish however, and it is unlikely or impossible that 100% of any one species will be able to achieve the swimming performance of fish which have been previously observed or tested to quantify swimming ability. This highlights the need for a balanced approach to fish passage provision, which considers the biological and ecological needs of migrating fish together with hydraulic and transport performance requirements and site limitations.

When compared to the guidelines provided for fish passage through culverts in NSW, Victoria and New Zealand, the Queensland Accepted Development Requirements for Operational Work that is Constructing or Raising Waterway Barrier Works (ADR) are prescriptive design requirements. The ADR does not provide the range of solutions which are identified in interstate and New Zealand fish passage guidelines. The Queensland State Development Assessment Provisions (SDAP) code for waterway barrier works which controls fish passage design requirements in Queensland (Queensland Department of Infrastructure, Local Government and Planning 2017) is generally outcome focused in its specification. However without a solid body of science available to proponents about what design specifications and parameters are required to be

met for effective fish passage, the tendency is for regulator and proponent to have to fall back on the prescriptive designs of the ADR.

In order to create and apply enhanced guidelines for fish passage at culverts, it is important to understand the requirements of fish and the current known barriers to fish passage which may be encountered in typical culverts. This body of knowledge can then be applied to the development of guidelines which consider possible treatments and how these might address the functional requirements of fish passage and other requirements such as hydraulic capacity and transport function.

2.2 FISH MIGRATION CHARACTERISTICS

2.2.1 BEHAVIOUR

Understanding the migration patterns of target fish species is key to determining key parameters relevant to fish passage design, including (O'Connor, Stuart & Jones 2017):

- the time of year when fish will be migrating
- the time of day when fish are active
- the flow conditions during migration attempts
- water temperature during migration attempts
- the life history stage of the target fishes during migration
- the swimming ability of the target fishes during migration
- the direction of migration (upstream/downstream)
- temporal criticality of the migratory event
- the importance of certain migratory events to the target fishes' life history.
- the number of fish migrating (biomass).

Many of the factors identified above are interlinked, and in terms of fish passage hydraulic design the overarching goal is to apply knowledge of these factors to determine appropriate hydraulic conditions within a culvert during times when fish passage is required. These target conditions are intended to allow passage by a reasonable proportion of the migratory fish population, which may vary depending on the species in question and the ecological objectives set (Franklin et al. 2018).

The typical behaviour of many Australian fish species includes cycles of migration during which fish will move between different habitats (Gordos et al. 2007; Lawson et al. 2010). Certain species of fish will undertake definitive patterns of migration between two or more distinct habitats, but all fish will need to move along the waterway which they inhabit to some degree (Gordos et al. 2007). Certain fish species which are classified as diadromous will migrate between fresh and saltwater at well-defined points in their life history (Miles et al. 2014). For fish which may be present in riverine habitats, there are generally four broad migration patterns that a species may fit in to (Harris et al. 2016; Kapitzke 2010b; Miles et al. 2014). These are:

- Potamodromous: live and migrate entirely within freshwater habitats. May migrate upstream or downstream as adults or juveniles depending on the behavioural patterns of the particular species.
 - Can be further categorised according to migratory direction at each life stage, and the habitats that they migrate between. Split into four groups (P1 through P4) by Kapitzke (2010b).
- Diadromous: migrate between fresh and saltwater habitats. Diadromous species are further categorised as:
 - Anadromous: primarily live in saltwater and migrate as adults to freshwater to spawn, juveniles born in freshwater must then migrate downstream.
 - Catadromous: primarily live in freshwater and migrate as adults to saltwater to spawn, juveniles born in saltwater must then migrate upstream (common in Queensland).

- Can be further categorised according to habitats that fish migrate between (upland or lowland habitats). Split into groups C1 and C2 by Kapitzke (2010b).
- Amphidromous: may move between freshwater and saltwater for non-reproductive reasons at defined times in lifecycle, may not necessarily be juvenile while migrating. Defined as group M1 by Kapitzke (2010b).

Kapitzke (2010b) undertook further classification of the migratory behaviours of fish found in Queensland, specifically the Tully-Murray catchment in northern Queensland. The author subdivided catadromous fish into two further behavioural groups and subdivided potamodromous species into a further four distinct behavioural groups.

In regard to seasonality (discussed further in Section 2.2.2), Kapitzke (2010b) makes the following statements based on observations made in the Tully-Murray catchment:

Catadromous:

- For group C1, adult downstream spawning migration occurs in spring to autumn (Nov – May) in association with increased stream flows, temperatures and day lengths. Juvenile upstream dispersal migration occurs during summer (Dec – April) during increased wet season stream flows, and adult upstream dispersal migration occurs during flood flows. Marine to upland habitats.
- Group C2 retain similar seasonal movement patterns but migrate over a much smaller distance as fish remain within lowland habitats. Marine to lowland habitats.

Potamodromous:

- For Group P1 within the Tully-Murray catchment, adult upstream spawning migration occurs during increased wet season stream flows (Nov – Mar). Juvenile and adult dispersal migration also occurs during wet season stream flows from Dec – April. Upland spawning.
- Group P2 is the opposite of group P1. Adult downstream spawning migration typically occurs during periods of increased stream flow, temperature, and day length which occur during spring and summer (Aug – Mar). Juvenile and upstream dispersal migration occurs during summer and autumn (Mar – May) and is typically linked to low stream flows. Lowland spawning.
- For Group P3, spawning typically occurs associated with increased temperature and day length, and during stable low flow conditions in winter, spring and early summer (July – Dec), and localised dispersal movement is associated with increased flows during Mar – May. Lowland to upland habitats.
- Group P4 are similar to Group P3 although spawning and growth is restricted to lowland waters. The timing of spawning and migration are practically identical to those for Group P3. Local spawning, lowland habitats.

Amphidromous:

- For Group M1, no adult spawning migration takes place, and juvenile/adult dispersal movement occurs associated with increased stream flow, although it is not obligatory for the life cycle of species.

These statements may not necessarily be applicable to fish behaviour in all regions of Queensland, or to all species which are not necessarily found in the Tully-Murray catchment, but they can be considered to provide a starting point to which other observations and research outcomes could be added as required.

Kapitzke (2010b) also classified each migratory behaviour in terms of the nature of migration, direction of movement and the fish movement and size related to the relevant life-cycle stage as shown in Table 2.1. Again, these classifications are not necessarily exhaustive, and there may be fish species which behave in manners outside of the descriptions given here.

Table 2.1: Fish movement direction categories: migration nature, movement direction, fish maturity and size, life-cycle stage

Movement direction	Description
Obligatory movement – essential migration for fish life cycle stages	

Movement direction	Description
AUS – Adult upstream spawning migration	Crucial upstream movement for adult potamodromous species en route to spawning habitats in upland or lowland freshwater reaches.
JUD – Juvenile upstream dispersal migration	Crucial upstream movement for juvenile catadromous or potamodromous species en route to growth habitats in upland or lowland freshwater reaches.
AUD – Adult upstream dispersal migration	Upstream movement for adult catadromous or potamodromous species following spawning in estuarine/marine or lowland freshwater reaches.
ADS – Adult downstream spawning migration	Downstream movement for adult catadromous or potamodromous species en route to spawning habitats in estuarine/marine or lowland freshwater reaches.
JDD – Juvenile downstream dispersal migration	Downstream movement for juvenile potamodromous species en route to growth habitats in lowland freshwater reaches.
ADD – Adult downstream dispersal migration	Downstream movement for adult potamodromous species following spawning in upland freshwater reaches.
Facultative movement – not essential for fish life cycle stages	
ALS – Adult localised spawning movement	Localised movement for adult potamodromous species en route to spawning habitats in local stream and wetland habitats.
JLD – Juvenile localised dispersal movement	Localised movement for juvenile potamodromous species en route to growth habitats in local stream and wetland habitats.
ALD – Adult localised dispersal movement	Localised movement for adult potamodromous species following spawning in local stream and wetland habitats.
LFM – Localised facultative movement	Localised movement for adult or juvenile amphidromous species migrating to and from estuary and lowland freshwater habitats on an occasional basis.

Source: Kapitzke (2010b).

Kapitzke (2010b) identifies AUS and JUD as the most important fish movements to provide for when developing fish passage requirements. These two movements are critical to the overall development and survival of the species which undertake each movement. AUS migration is generally temporally critical, with little tolerance for delay to passage once the fish are developmentally ready to spawn. It is thought that JUD migration is more tolerant to a waiting period if flows through a certain fish passage barrier must reduce to a certain level before successful passage can be achieved (Kapitzke 2010b), but consideration must be given to possible predation during waiting periods. AUD is also highly important to fish lifecycles but fish undertaking these migrations may typically be stronger swimmers.

Based on the above observations, it could be concluded that AUS and JUD migrations should be considered first and foremost when considering fish ability for hydraulic design. An extreme approach where fish passage by these migrators was the only performance criteria used for determining acceptable fish passage conditions within a culvert may not be ecologically acceptable, however. Facultative migrations are not directly critical to the life cycle development of fish, but these migrations should not be considered completely unimportant, and a situation where facultative migrators are completely excluded from passing a certain barrier should be avoided (phone conversation with T. Marsden, Feb 2020).

Table 2.2: Generalised fish movement direction for fish movement groups: migration nature, movement direction, fish maturity and size, life-cycle stage, and including migration timing and flow for fish species of the Tully-Murray catchment

Fish movement group	Upstream movement – obligatory			Downstream movement – obligatory			Localised movement ALS/JLD/ ALD/LFM
	Adult spawning AUS	Juvenile dispersal JUD	Adult dispersal AUD	Adult spawning ADS	Juvenile dispersal JDD	Adult dispersal ADD	
Group C1 – Catadromous species, marine to upland habitats		✓ _F	✓	✓ _F			
Group C2 – Catadromous		✓ _F	✓	✓ _{L/F}			

Fish movement group	Upstream movement – obligatory			Downstream movement – obligatory			Localised movement ALS/JLD/ ALD/LFM
	Adult spawning AUS	Juvenile dispersal JUD	Adult dispersal AUD	Adult spawning ADS	Juvenile dispersal JDD	Adult dispersal ADD	
species, marine to lowland habitats							
Group P1 – Potamodromous species, upland spawning	√ _{L/F}				√ _F	√ _F	
Group P2 – Potamodromous species, lowland spawning		√ _{L/F}	√ [*]	√ _{L/F}			
Group P3 – Potamodromous species, local spawn. lowland to upland habit.	(√ _L)	√ [*]	√ [*]				ALS/JLD/ ALD _{L/F}
Group P4 – Potamodromous species, local spawning, lowland habitats		(√)	(√)		(√)	(√)	ALS/JLD/ ALD
Group M1 – Amphidromous (freshwater vagrant) species							LFM _{T/L}
Legend	F: Predominantly flood flow (wet season) conditions			*: Substantial movement for some species			
	L: Predominantly low streamflow conditions			(): Tentative categorisation			
	T: Tidal flow conditions			?: Unknown			

Source: Kapitzke (2010b).

Kapitzke (2006) also undertook classification of fish species found in the Tully-Murray catchment based on the migratory classifications detailed in this section. An extract from this dataset is provided in Appendix B.2. The dataset is not complete, and there was not comprehensive data available for all species in the catchment at the time of the classification exercise. It does provide a useful synthesis of available data however, which may be applied to other catchments where similar fish species compositions are found.

Potamodromous fish may be found within coastal or inland waterways, while fish which spend some part of their migratory cycle within marine habitat will naturally be found within waterways which have connectivity to the ocean within the migratory range of the species, i.e. most rivers flow into a marine environment eventually, but it would be very unlikely to find diadromous fish in the upper reaches of the Murray-Darling Basin.

Potamodromous fish which fall into groups P1 and P2 may not rely on a defined range of migration for survival, but barriers to potamodromous migration may result in reduced migratory ranges for fish and degradation of habitat due to either overabundance of fish in inhabited areas or removal of fish from the ecosystem in areas which have been cut off by barriers (Gordos et al. 2007). These effects can then negatively impact the wellbeing of the fish population and may be highly undesirable depending on the conservational value of the species in question.

Small barriers in coastal rivers and streams including causeways and culverts may have a large impact on the populations of catadromous species, as small-bodied weak juveniles which have been born in saltwater

will generally have poor swimming ability which leaves them unable to access upstream habitat (Harris et al. 2016). This can have a major impact on the population and ecosystem health of the fish and waterway in question.

2.2.2 MIGRATORY TRIGGERS

The undertaking of migration is often linked to certain triggers, which vary between different species of fish and the habitats which they inhabit. Some common triggers include (Kapitzke 2010b):

- increased waterway flows due to rainfall or environmental releases from dams where applicable
- fish reaching a certain stage of maturity
- changes in water temperature
- changes in photoperiod (day length).

As discussed previously in Section 2.2.2, migratory triggers may vary between different species of fish, although there are some generalisations which can be made. Where migratory events are triggered due to environmental flow releases from dams, the cooler temperature of the released water may lead to reduced swimming capacity for migratory fishes, as discussed in Section 2.4.6. There are also some species of fish which migrate during periods of lower flow and lower water temperature, with one such example being lungfish (Queensland Department of Agriculture, Fisheries and Forestry 2014).

Species that migrate in response to increased flows are likely to require passage at relatively high discharge magnitudes. It has been reported that many species of fish will attempt passage through structures in the tail of high discharge events (Cabonice, Wang & Chanson 2018), meaning that flow will be elevated but it will likely be considerably lower than design discharge for hydraulic capacity. This maximum fish passage flow may vary depending on the regionality and flow regime of the waterway that the structure is located in as discussed in Section 2.2.4. While the theory that fish attempt migration during less-than-design flow conditions in the lead and lag of rainfall events has been anecdotally confirmed by a fish passage expert (phone conversation with Dr Jabin Watson, Jan 2020), there does not appear to be any significant research outcomes which support the theory.

The triggers discussed above are generally related to migratory events which form a defined part of a fish's lifecycle history. Facultative movements undertaken by juvenile or adult fish may be triggered by other factors, such as the need to find food, escape from predators or enter favourable sections of a stream during times of drought (Kapitzke 2010b). These movements are most likely to occur during periods of low-medium flow in a stream, where prevailing conditions are relatively stable. If the free movement of these fish within the waterway is impeded, it may lead to negative impacts such as reduction of fish population and degradation of the environment due to the absence of the species. These movement requirements are not currently well-understood, however.

2.2.3 SEASONALITY

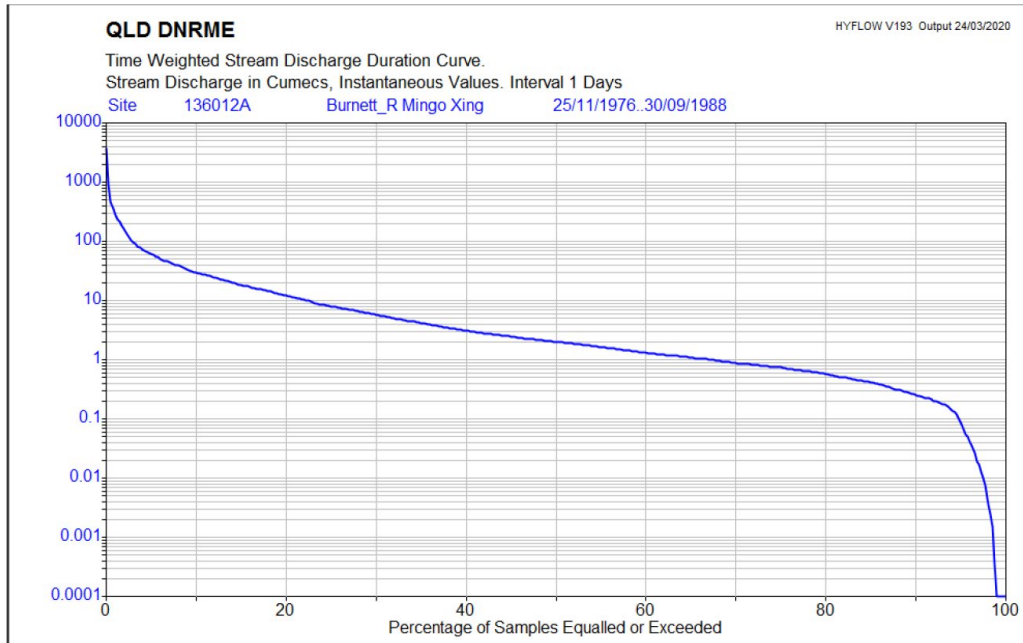
The seasonality of migration for individual fish species may vary significantly, even within a selected waterway system of interest (Kapitzke 2010b; Sinclair Knight Merz & SunWater n.d.). Many species of fish will migrate when flows increase due to rainfall (Amtstaetter et al. 2017). This will often be linked to defined wet season rainfall in northern Queensland, or periods of high rainfall linked to climate events such as La Niña. Indeed, river flows within Queensland and Australia as a whole, are typically influenced by cycles of drought and flood, with migrations occurring during periods of high flow (Harris et al. 2016). This means that fish surveillance at a structure during drought or dry season periods may not be indicative of the fish utilisation which occurs during extended periods of rainfall.

Waterways which only flow during the wet season may act as fish habitat during this period (Kapitzke 2010b). Ephemeral waterways are typical across Queensland. In order to determine whether a given stream provides fish habitat, it is important to undertake monitoring during the wet season (in tropical Queensland) or otherwise during periods of sustained rainfall which will encourage fish migration. If there are

no fish evident during these periods, or if fish are achieving acceptable passage under current conditions, it may be reasonable to assume that provision for fish passage is not required.

The seasonality of stream flows may be determined in some cases through investigation of river gauge data which is managed by the Queensland Department of Natural Resources and Mines and Energy. An example streamflow duration curve for the Burnett River is shown in Figure 2.1. This is a typical curve for Queensland conditions, which shows that the river experiences relatively low base flow conditions for much of the time, which are bookended by rarer periods of high flows which are likely associated with wet season rainfall events, and periods of very low flow which are likely associated with the dry season and potentially drought conditions.

Figure 2.1 Stream discharge duration curve for Burnett River



Source: Queensland Department of Natural Resources, Mines and Energy (2020).

While migration on increased flows and in the warmer months of the year is most common, monitoring and observation in Queensland has reportedly shown that this is not always the case, with fish movement occurring practically year-round and over most flows (Queensland Department of Agriculture, Fisheries and Forestry 2014). Some species have been shown to move during winter months, which may mean that the impact of reduced temperature on swimming ability needs to be considered as discussed in Section 3.3.4. In general, it appears that the range of flow conditions that fish need to migrate during has not been particularly well defined in Queensland, or other Australian states.

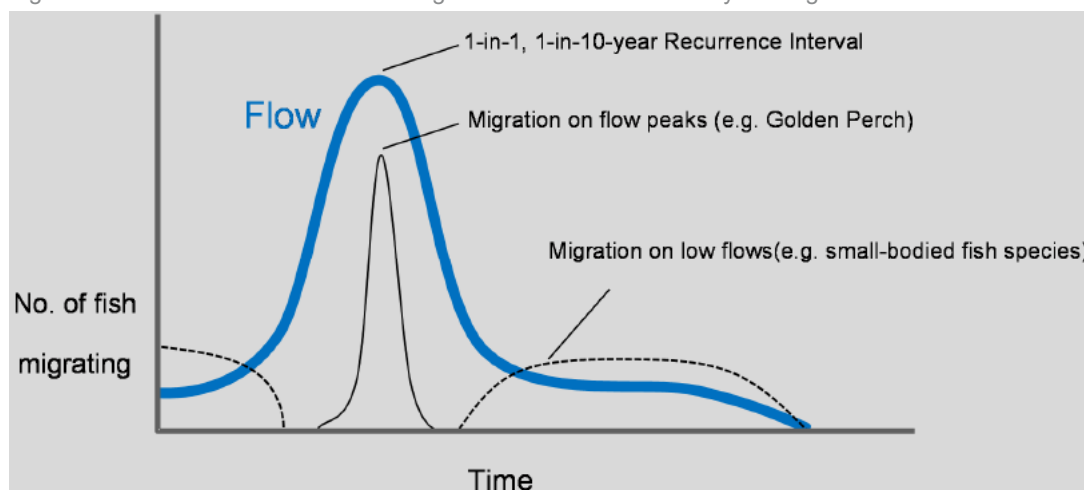
Data relating to fish movements in Queensland and Australia has largely been collected as part of studies on fishway effectiveness, which generally do not address the purpose and importance of migrations (Pusey, Kennard and Arthington 2004). Some limited observations of fish movement behaviour have been made during studies of fishway effectiveness at sites along coastal eastern Queensland. One such study was conducted at a tidal barrage on the Fitzroy River at Rockhampton and showed that fish were migrating at both low flows (exceeded 82% of the time) and high flows (exceedances from 41% to 14%) (Marsden, Berghuis & Stuart 2017). Observations for this study also showed that fish were attempting movement during flood flows (exceedances from 3% to 1.6%), with the highest daily numbers of Hyrtl's tandan and long-finned eels captured during these flows, as well as high numbers of blue catfish. Most specimens recorded for the tandan and blue catfish were greater than 100 mm in length.

Certain species of fish show defined patterns of migration which are most prevalent during certain months of the year. Generally, this temporal variance in migratory patterns has not been comprehensively quantified for a wide range of Queensland fish species and data availability is limited to species found in selected catchments where past research has been focused. Available datasets include:

- Limited data relating to the timing of fish movements for common Victorian fish species is provided by O'Connor, Stuart, & Campbell-Beschoner (2017), with little crossover with Queensland species except for some which are found in the Murray-Darling Basin.
- Kapitzke (2010b) provides details on the seasonal movements of fish found within the Tully-Murray catchment in the dry tropics of north Queensland.
- Sinclair Knight Merz & Sunwater (n.d.) provides some details of fish movement timing for Queensland species found within the Fitzroy River catchment, which are likely based on field observations.
- Varying levels of detail relating to the movement patterns of Queensland freshwater fishes (primarily those found in coastal systems) is provided by Pusey, Kennard & Arthington (2004).

The seasonality of migration in the Murray-Darling Basin is discussed by O'Connor, Mallen-Cooper & Stuart (2015). They state that freshwater fish migrate according to various triggers including changing flow and temperature conditions. Some large bodied fish (such as adult golden perch) migrate on flows that correspond with a 1-year ARI or greater, while smaller-bodied fish and juveniles are likely to migrate on lower flows. Figure 2.2 shows a comparison of flow condition vs. numbers of fish migrating for the lower Murray-Darling Basin.

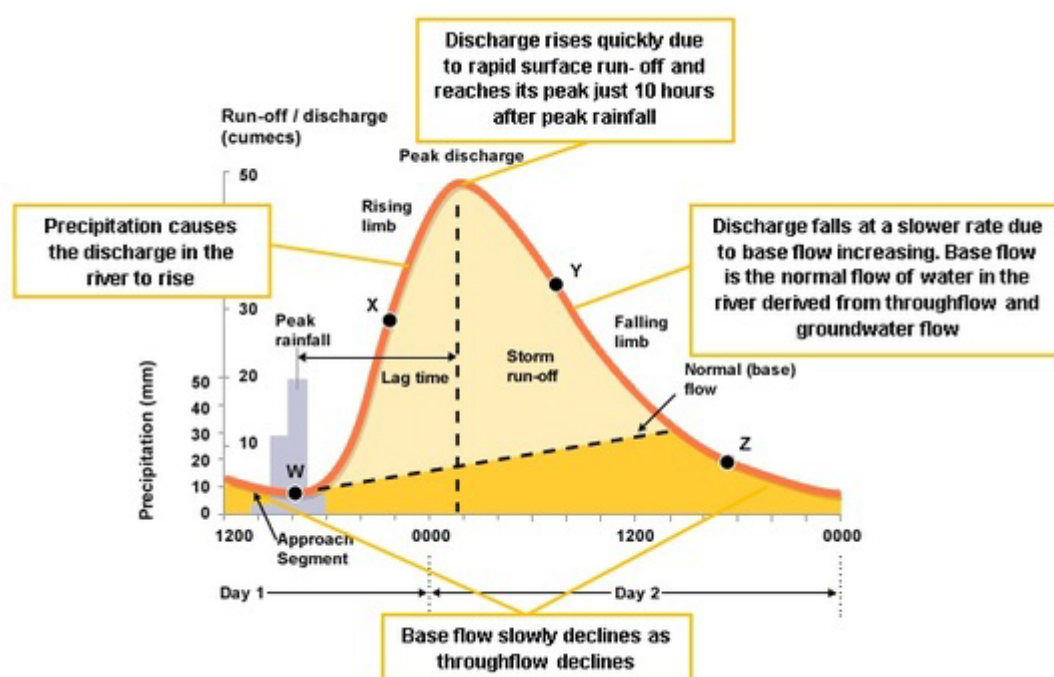
Figure 2.2 Flow conditions vs fish migration events: lower Murray-Darling Basin



Source: O'Connor, Mallen-Cooper and Stuart (2015).

While migration in response to increased flows due to rainfall is widely identified in the literature, the timing of fish movements during these flow events has generally not been clearly defined. It has been postulated that fish will generally be moving during the lag time of a discharge event as illustrated in Figure 2.3, and not during the peak discharge (Cabonce, Wang & Chanson 2018), but this does not appear to be backed up by any significant research. Fish may also attempt passage during the falling limb of the hydrograph as flows return to base flow. Where the peak discharge occurs for a relatively short duration it may be acceptable for fish to undergo a waiting period until discharge drops to an attemptable level, but this period should be as short as possible to avoid possible predation (Marsden, Berghuis & Stuart 2017).

Figure 2.3 Typical flood hydrograph demonstrates the anatomy of a flow event in a waterway following rainfall in the catchment



Source: *The British Geographer* (n.d.)

2.2.4 REGIONALITY

There is some limited distinction between the fish species which can be found in coastal streams east of the Dividing Range (the north-east coastal division), and those which can be found in the Murray-Darling Basin and other more ephemeral western waterway systems such as Cooper Creek. Species found west of the Great Dividing Range are inherently potamodromous, while species found east of the Range can be either potamodromous or diadromous. There are some species which are unique to the MDB, Lake Eyre system and/or other western waterways, but there are many cases of crossover between the potamodromous species found on either side of the Range, such as the potamodromous Golden Perch which is found in the upper Murray-Darling Basin and the Cooper Creek system, but also has a subspecies which is found in the Fitzroy River system (Atlas of Living Australia n.d.). Another example of a species found on both sides of the Range is the Silver Perch which is native to the Murray-Darling Basin but has been introduced to coastal rivers in south-east Queensland (McGrouther 2019b). Many species of fish which were originally native to the Murray-Darling Basin and western river systems have entered coastal systems through river capture events and other mechanisms.

Coincidentally, Golden Perch (*Macquaria ambigua*) is one of the weakest swimming juvenile species tested by Watson et al. (2019), and would be expected to be unable to gain passage by swimming at critical speed against a velocity of 0.3 m/s as a juvenile. Based on the initial observations of Mallen-Cooper (1999a), Golden Perch appears to fall into the potamodromous migration Group P1, which is categorised by adult fish migrating upstream to spawn and juvenile larvae drifting downstream, although this group does not comprehensively explain observed behaviours. Sub-adult Golden Perch which are greater than one year old then migrate upstream in stages to account for their larval drift (Mallen-Cooper 1999a). Adult spawning migration occurs during times of high flow through spring and summer, and juvenile upstream migration occurs during high and low river rises from spring to mid-autumn.

Despite these observations, Mallen-Cooper (1999a) notes that Golden Perch have been observed spawning in still pool environments, and 20% of fish tagged during a migration study hardly moved from the tagging site. Based on these observations, migrations by adults and juveniles may be somewhat facultative rather

than a crucial part of the species' life history (thereby potentially fitting more closely in group P3 as defined by Kapitze (2010b)). These migrations are however likely to be important with regard to supporting the overall survivability of the species and maintaining population over a diverse range of habitat.

Mallen-Cooper (1999a) noted that Golden Perch, while declining in population somewhat throughout the Murray-Darling Basin, has been relatively successful compared to other species such as Silver Perch in the Murray-Darling Basin or barramundi in coastal streams of Queensland.

The flow regime of inland streams is typically quite different to that of coastal streams, with inland streams typically being more ephemeral than coastal streams (O'Brien et al. 2016). Waterways in western Queensland will also typically have different flood flow regimes to east coast waterways (phone conversation with T. Marsden, Feb 2020):

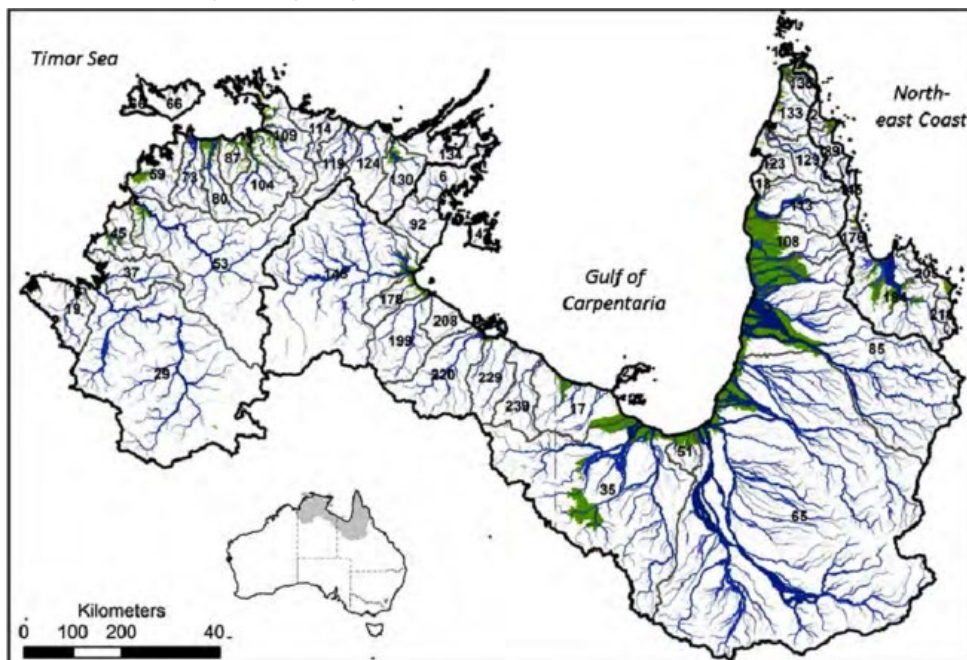
- Western systems may experience low ARI high magnitude flows for weeks at a time after significant rainfall events. These flows may also be relatively low velocity due to the wide floodplains and flat terrain, but constriction at culverts is likely to increase stream velocities relative to the floodplain velocity.
- Eastern systems are more likely to experience relatively brief low ARI high magnitude flow events (with associated high water velocities) where water is quick to overtop a culvert and/or quick to recede resulting in periods of high flow which may last for hours rather than days.

For eastern systems, these observations mean that fish may be more likely to gain passage over the top of a culvert during periods of high flow, although expected water depth and the presence of zones of reduced velocity in the flow path over the structure may need to be considered. If there is a short period of time between the initiation of high flows and culvert overtopping there may be a case for less stringent fish passage design requirements within the culvert under high flow conditions. This is less likely to be viable for western systems where culverts are typically designed to pass long-duration higher flows beneath roadways during the tail of large flow events, and roughening elements are likely to be needed in culverts in these areas in order to reduce bankside water velocities. These elements are necessitated by the fact that fish in western systems, including those which are juvenile and/or small-bodied, are likely to be migrating during extended periods of high flow (phone conversation with T. Marsden, Feb 2020). These movements are likely to be critical to repopulation and survival of fish communities due to the highly unpredictable nature of flow events in western systems (Queensland Department of Agriculture, Fisheries and Forestry 2014).

Differences in flow regimes were reportedly taken into account when developing the DAF *Queensland Waterways for Waterway Barrier Works* spatial layer which classifies streams according to fish passage criticality (O'Brien et al. 2016). Limitations of the spatial layer have been recognised by both DAF and TMR. There is currently an agreed process between TMR and DAF for re-assessing waterways where waterway categorisation is questioned. At the time of writing DAF are currently undertaking a review of the waterway spatial layer to address limitations of the current version.

While this section has so far considered a dichotomy between eastern coastal Queensland, and inland Queensland to the west of the Great Dividing Range, Tropical North Queensland (partially illustrated in Figure 2.4), including eastern coastal rivers and those which flow into the Gulf of Carpentaria, can be considered as a separate region which is habitat to some species not found elsewhere in Queensland. Migratory behaviours in this region are often characterised by response to defined wet-season rainfall events (Kapitze n.d.), with one such example being the Plotosid Catfish (*Neosilurus hyrtlui* and *Porochilus rendahl*) which is widely distributed throughout northern Queensland. Adult specimens of this potamodromous species has been observed to be migrating upstream within six hours of initial stream rises after the onset of summer rain in the Townsville-located University Creek waterway (Kapitze n.d.).

Figure 2.4 Tropical North Queensland (Gulf of Carpentaria and part of North-east coast divisions) as defined by Pusey et al. (2017)



Source: Pusey et al. (2017).

There is considerable focus in the literature on the migratory behaviour of diadromous species, but there has been less analysis of potamodromous migrations. Within Australia, some of the most comprehensive analyses of potamodromous migration have occurred with a focus on movements within the Murray-Darling Basin (Mallen-Cooper 1999a).

It has been found that the scale of the migrations that a certain fish species undertakes is related to swimming ability. Fishes which migrate on a macro scale (i.e. > 500 km) are generally stronger swimmers than fish species which migrate on a meso (i.e. ~100 km) or micro scale (< 10 km) (Watson et al. 2019). Fish which migrate on a macro scale are most likely to be found in the Murray-Darling Basin and other extensive western Queensland systems.

The preferred habitats and behaviours of many freshwater fish species in Queensland are described by the book *Freshwater Fishes of North-Eastern Australia* (Pusey, Kennard & Arthington 2004). This book contains information on the regionality of species, stream substrate types that species are found in (sand, gravel etc.), typical locations in the water column and the stream velocities in places that species have been found inhabiting. Migratory behaviours are also described, including life cycle strategies, triggers and migration timing. This book may provide a valuable resource for examining the movement habits of weaker swimming species which are likely to be controlling of culvert design. Attempting to take into account the characteristics of every fish species in a selected catchment may be unrealistic however, and it is currently unclear which species and life stages should form the focus of targeted design efforts, although the weakest swimmers may need to be considered in the first instance.

2.3 FISH BIOLOGY CHARACTERISTICS

The biological characteristics of the fish that a given culvert needs to provide passage for are key to developing an effective design (O'Connor, Stuart, & Jones 2017). Key characteristics include (O'Connor, Stuart, & Jones 2017):

- swimming ability
- size of migratory fishes
- seasonal biomass or abundance of migrating fishes

- life-history traits
- swimming behaviours.

Fish biology characteristics relevant to passage are often interlinked with migratory behaviour and the life history approach of the fish species in question, meaning that the discussions in Section 2.2 should be kept in mind. For example, fish which migrate against flood flows while juvenile, are likely to be stronger swimmers than species which do not migrate during flood conditions. A simple way of thinking about it is that fish migration characteristics will define when a fish is likely to arrive at a structure, and both fish biology and migratory characteristics will contribute to the fish's chance of passage success. The primary topics of discussion in the following sections are swimming ability and swimming behaviours which contribute to passage success. The size of migratory fishes is considered as linked to swimming ability.

2.3.1 SWIMMING ABILITY

General

Fish swimming ability is typically quantified in terms of the maximum water velocity that a fish can successfully swim against without tiring and being washed downstream (this equates to being washed completely to the back of the test apparatus during laboratory swimming tests) which may be expressed in terms of the achievable number of fish body lengths per second (L_{BS}^{-1}) for a specific size and/or species of fish, or as an absolute velocity measurement (e.g. ms^{-1}) (Kern et al. 2017; Watson et al. 2019). Body lengths per second has been a commonly used metric in the past, but more recent research has focused on reporting results in ms^{-1} as this is more relevant to hydraulic engineering applications.

The swimming behaviour of fish can be categorised into three patterns each with a corresponding achievable velocity and period for which it can be sustained (Humphries & Walker 2013; Hyde 2007; Kapitzke 2010b; Kern et al. 2017; Watson et al. 2019).

The swimming modes can be summarised as follows:

- Burst or sprint speed (U_{sprint}): sustained for less than 20 seconds or several metres (may be a shorter distance depending on water velocity) before fishes become fatigued and need to stop and rest. Potentially used to traverse high velocity zones between resting areas in a fish passage structure.
- Sustained or critical speed (U_{crit}): sustained for several minutes or 12–14 m (may be a shorter distance depending on water velocity) before fishes become fatigued. Potentially used to gain passage against a sustained challenging velocity through a fish passage structure of length which does not exceed the distance over which a target fish can swim at sustained speed against the intended water velocity without tiring.
- Cruising speed: able to be sustained indefinitely (200+ minutes). Used when swimming in unchallenging velocity conditions or resting.

There is some variation between authors as to where the lines are drawn between swimming modes in terms of achievable period of exertion, and traversable distance. These factors will also vary between different species of fish.

Historic study of fish biology has found that fishes will use different types of muscle to achieve different swimming modes (Watson et al. 2019). Achievable speeds for each method of swimming vary according to fish size, specific characteristics of the species in question and the developmental stage of the individual fish (Kopf, Humphries & Watts 2014), with small-bodied fish and juveniles of larger species typically being weaker swimmers. Many catadromous and potamodromous species of Australian fish migrate upstream while juvenile (and small-bodied), so it is prudent to consider the swimming ability of juvenile fish (Hyde 2007; Kapitzke 2010b).

The performance of a certain fish in a certain structure is likely to be highly context-specific, as fish may elect to use any combination of swimming ability to attempt passage depending on the biotic and abiotic conditions in and around the structure (Kern et al. 2017; Watson et al. 2019). Fish may also experience

cumulative fatigue if a certain stream has multiple in-stream structures which present a challenge to fish passage. This may lead to reduced swimming performance at upstream structures.

Certain treatments including baffles are designed on the basis of providing low velocity resting areas for fish in between areas of relatively high culvert channel velocities (Kapitzke 2010e). These treatments rely on fish to use a so-called 'burst and rest' approach to passage wherein fish swim at their U_{sprint} speed for short distances in between areas where they can rest at their cruising speed (or station hold – Section 2.3.2) without being washed downstream (Kapitzke 2010e; Wang et al. 2016). Fish passage success rates using this method are variable and require the treatment to be designed such that the critical swimming speed and time to fatigue of target fish are well matched to the conditions provided during flows when fish passage is expected.

Testing methods for the determination of swim speed

The determination of U_{sprint} and U_{crit} is typically achieved through testing wherein fish are introduced to a flume, then after a period of acclimatisation the water velocity is increased by a certain increment over a certain time period. Tests for U_{sprint} involve increasing velocity over short time intervals (e.g. 0.5 m/s every 10 seconds), while the determination of U_{crit} involves increasing velocity over longer intervals (e.g. 0.5 m/s every 5 minutes) (Watson et al. 2019). In contrast, endurance tests are conducted by swimming fish at a fixed velocity and measuring the amount of time it takes for fish to become fatigued. For example, three different fixed velocities were used by Watson et al. (2019), which were determined based on the results of the U_{crit} tests for each species of fish tested.

Different researchers have applied varying methods to the determination of U_{sprint} and U_{crit} which may have led to results which are not readily comparable between studies (Watson et al. 2019). Protocols for testing may vary in terms of the time and velocity increments that tested fish are subjected to. Experimentally determined swimming ability may vary according to biotic factors such as age, population, sex and seasonal differences as well as abiotic factors relating to test setup including flume design, fish acclimatisation and time/velocity increments applied (Kern et al. 2017). The flow conditions within the test apparatus were found to have a significant impact on the measure of endurance for the three small-bodied or juvenile Australian fish species tested by Kern et al. (2017).

To account for these variations, Watson et al. (2019) conducted a variety of performance tests which incorporated a range of volitional and non-volitional measures while using consistently configured test equipment. They used a 12 m long by 0.5 m wide hydraulic flume channel to test endurance swimming ability, which is comparable to a box culvert in terms of shape and hydraulic behaviour, although not as wide as a typical box culvert used for transport applications. A recirculating flume was used for U_{crit} and U_{sprint} experiments. The same 12 m hydraulic channel was also used for several other fish swimming ability and behavioural studies by Wang and Chanson (2018).

Various University of Queensland (UQ) researchers have undertaken a range of fish swimming experiments, primarily using Duboulay's rainbowfish and silver perch specimens (Chanson 2019; Watson et al. 2018). They have used the same open surface swim tunnel that was used for culvert traversability tests by Watson et al. (2019). Pure trials of swimming performance have not been the focus of this research, rather most experiments have focused on the testing of various baffle configurations and channel roughening, as well as enhancing understanding of fish hydrodynamics in general. This work is primarily discussed further in Section 2.4.1 which discusses water velocity as a fish passage barrier and potential remediation options.

In order to make best use of the results from swimming ability tests under laboratory conditions, the differences between the conditions which will exist within the culvert or other fish passage structure and the laboratory conditions must be well understood (Kern et al. 2017). Ideally, laboratory data should be complemented by swimming performance data collected in the field, although such field data may be context specific depending on the conditions it is observed under. To date, there appears to have been very little in the way of field trials which have focused on the swimming performance of Queensland, or Australian fish species, with one notable exception being the work by Mallen-Cooper (1999b). This work was completed within a fishway installation however, which may not be directly representative of the type of hydraulic

conditions that exist in a typical culvert. Overall, determining a definitive measure of fish swimming ability is very complicated, and it is usually preferable to err on the side of conservatism when designing for target hydraulic conditions in a fish passage structure.

Swimming ability studies for Australian fish species

Swimming performance data for Australian fishes has been historically limited, but the study completed by (Watson et al. 2019) and other recent studies (Kern et al. 2017; Kilsby & Walker 2010; Kopf, Humphries & Rodgers et al. 2017; Watson et al. 2018; Watts 2014) have begun to fill this data gap. Historic study of fish swimming performance has been carried out mainly for species found in the Murray-Darling Basin (Mallen-Cooper 1999b; Mallen-Cooper 2001). Based on the work of Mallen-Cooper (2001), a prolonged swimming speed of 3 body lengths per second was recommended for Australian native fish, with design swim speeds of 0.15 m/s for fish less than 80 mm in length and 0.75 m/s for fish greater than 250 mm in length (Kapitzke 2010b).

In order to overcome the fragmentation which can occur due to variations in test setup between different studies, Watson et al. (2019) set out to quantify the swimming ability in terms of U_{crit} and U_{sprint} for 21 species of Australian fish using consistent test conditions for each species. The species tested represent a diverse range of morphologies and ecological traits which allows the experimental results to be applied to fish with similar physical or behavioural traits. To date, Watson et al. (2019) has been the most wide-ranging study of fish swimming ability conducted in Australia. The species tested by Watson et al. (2019) were intended to represent NSW species, but there is reasonable crossover with common Queensland species (refer to Appendix A for details of key Queensland species).

Watson et al. (2019) undertook culvert traversability modelling based on the measured 25th percentile U_{crit} velocity for each fish species tested. From this, a relationship was developed between culvert length, water velocity and the swimming ability of 75% of the fish within the size range tested for each species. This culminated in the development of a chart which can be used to determine an appropriate culvert length and maximum velocity which would theoretically allow 75% of the fish tested to gain passage (provided in Appendix B.1.1).

Fish were also swum in a free surface rectangular swim tunnel (12 m L x 0.5 m W) which is hydraulically similar to a box culvert, although with a smaller width. Watson et al. (2019) generated a measure of 'culvert traversability' by determining whether the studied fish species could swim 8 m along the free surface swim tunnel against a set bulk water velocity. Eight m was selected based on the typical culvert length in NSW beneath a 2-lane rural road based on advice from NSW Roads and Maritime Services.

Interestingly, Watson et al. (2019) found that the 0.3 m/s maximum velocity during base flow recommendation for fish-friendly culvert design in NSW, Victoria and Queensland is fairly well-supported by the results of the traversability modelling, with only four species of fish tested expected to be unable to pass an 8 m culvert under a velocity of 0.3 m/s (*M. adspersa*, *M. ambigua*, *P. grandiceps* and *R. bikolanus*). Except for *M. ambigua*, these species have shown station holding behaviour in an experimental environment, meaning that passage against higher velocities may be possible in real-world situations, although this is yet to be quantified. They found that body length combined with depth station (position in the water column that the fish occupy: either benthic (stream bed), pelagic (centre), or surface-swimming), body shape and/or tail shape were the best predictors of swimming ability for the swimming performance of an unknown test fish. Body length was found to be the most important factor, with the addition of other characteristics best suited to providing additional certainty to estimates made based on body length. These are key findings which could potentially be applied to the determination of swimming ability for fish which have not been tested.

It should be noted that the range of body sizes tested by Watson et al. (2019) (Table B.3, Appendix B.1) is generally not representative of the fish sizes at the first 'important life stage' for key Queensland fish species identified by T. Marsden (Table A.1, Appendix A). Email correspondence with J. Watson from UQ in February 2020 confirmed that it may not be possible to use the results presented in Watson et al. (2019) to predict the swimming ability of fishes at the first life stage. It is unclear whether any of the species identified

in Table A.1, Appendix A need to migrate upstream at their first important life stage, and it could be assumed that the small-bodied fishes would be relatively weak swimmers at this life stage.

It is thought that laboratory experiments will generally provide a conservative estimate of fish swimming ability (Kapitzke 2010b; Kern et al. 2017; Watson et al. 2019) which may result from the setup of the test equipment or other limitations such as fish source (i.e. wild vs commercially bred, with wild fish sometimes exhibiting greater swimming ability). This can be an ecological positive in that structures may achieve better fish passage results than are expected, but can be economically undesirable as maximum velocity requirements indicated by testing may be more stringent than is actually required, resulting in increased costs and narrowing of potential options (Kern et al. 2017).

Prior to the work of Watson et al. (2019), there have been several other studies of swimming ability carried out on Australian fishes. These studies have generally focused on a small handful of species, mostly those which are found either in the Murray-Darling Basin or other parts of southern Australia, although there are some species studied which are found in southern coastal Queensland. These studies have been carried out with varying methodologies and fish characteristics meaning that the results from each study may not be directly comparable.

Kilsby and Walker (2010) studied the swimming ability of three small-bodied species, namely common galaxias, Australian Smelt and flat-headed gudgeon. They used a recirculating flume for testing which was 0.5 m long, 0.19 m deep and 0.16 m wide, which would have produced hydraulic conditions quite different to what would be encountered in a waterway or standard culvert. They found that the common galaxias ($U_{crit} = 0.5$ m/s) and Australian Smelt ($U_{crit} = 0.5$ m/s) swam more strongly than the flathead gudgeon ($U_{crit} = 0.27$ m/s), noting that 0.5 m/s was the maximum velocity tested which means that U_{crit} may have been higher for the two former species. They note that while the flathead gudgeon was a weaker swimmer, it was better able to locate areas of lower velocity within the flume, an observation which is also made by later researchers who have studied small bodied Australian fishes.

Some of the earliest determination of Australian fish swimming ability was undertaken by Mallen-Cooper (1999b), who studied the swimming ability of fish traversing a slot fishway which was installed at Torrumbarry in the Murray-Darling basin to allow fish passage over a weir. The design of the fishway included a 20 m connecting channel which the study fish needed to traverse. The water velocity in this channel ranged from 0.2 m/s at the edges to 0.33 m/s in the centre. Mallen-Cooper (1999b) stated that this velocity could be used as an initial guide for fish passage in culverts for the species and sizes of fish which migrate along the Murray River and 'possibly for other similar non-salmonid fishes'. This advice was taken up by the former NSW Fisheries, who have adopted the recommended maximum velocity of 0.3 m/s for new and refurbished culverts (Fairfull & Witheridge 2003). The native fish species studied by Mallen-Cooper (1999b) included:

- Golden perch
- Silver perch
- Bony herring
- Australian smelt (could not ascend the fishway and therefore could not enter the channel).

Carp were also observed but given that this is an invasive species its passage should not be catered for. Despite this, adults were observed to be capable of passing the fishway, while juvenile carp were generally unable to.

Of the above fish, the bony herring (also known as the bony bream) is the most widespread throughout Queensland, with widespread sightings made throughout freshwater drainages in Queensland, the Northern Territory and the Murray-Darling basin (McGrouther 2019a). Golden perch are less widespread but have been sighted in freshwater drainages throughout southern and central Queensland, primarily in the upper Murray-Darling basin (Atlas of Living Australia n.d.). Silver perch are primarily found in the Murray-Darling basin, but some have been introduced into Queensland coastal rivers (McGrouther 2019b). The fish studied by Mallen-Cooper (1999b) could therefore be considered somewhat representative of typical fish found in the upper reaches of the Murray-Darling basin in Queensland.

The sizes of fish that were observed to be using the fishway ranged from 120–600 mm in length, meaning that smaller species of fish were not represented. The Australian Smelt which could not ascend the fishway was primarily less than 40 mm in length, but it is unknown whether the smelt could have negotiated the connecting channel with velocities of up to 0.33 m/s, as they could not ascend the lower fishway (which operates at a higher velocity than the channel).

Other researchers have postulated that the works completed by Mallen-Cooper (1999b) are not comprehensive enough to apply the passable velocity assumption to all species of fish, particularly innately small bodied fish and those which are small bodied as juveniles (Rodgers et al. 2014). Kopf, Humphries and Watts (2014) studied the swimming performance of Murray-Darling fish larvae, which has some overlap with the species studied by Mallen-Cooper (1999b), but since the larvae tested were primarily downstream migrators at the life history stage studied, the results are not directly relevant to upstream culvert fish passage.

Mitchell (1989) studied the swimming performance of five diadromous migrating species of fish found in New Zealand using laboratory flume testing. They concluded that juveniles of these species (30–80 mm in length and with the exception of sea mullet) could likely gain passage against a velocity of 0.3 m/s if the obstacle was less than 15 m in length. One of the species tested (common galaxias) is also found in southern Australia, and another (New Zealand Smelt) is similar to the Australian Smelt which is found in the Murray-Darling Basin and southern coastal waterways in Queensland. This study appears to be the earliest evidence for the recommended maximum velocity figure of 0.3 m/s for culverts which features in most Australian fish passage guidelines.

Some generalisation on fish swimming ability for species found in the Tully-Murray catchment is provided by Kapitzke (2006) as shown in Table 2.3. Some further data from this project relating to swimming speed in provided in Appendix B.2.1. The prolonged (critical) speed data has mostly been estimated based on simple comparison of distance travelled versus time for fish observed in the field and fish body size, while burst speeds have primarily been estimated based on the critical speed data. This means that the data is potentially conservative (Kapitzke 2006), but there is no comprehensive basis for this assumption to be made upon, and the data should not be considered fully representative of field swimming performance.

Table 2.3: Nominal fish swim speeds for Tully-Murray fish community – upstream movement

Fish movement capability group	Common length of fish	Prolonged speed – nominal	Burst speed – nominal	Comment
AUS – Adult upstream spawning migration (fish movement groups P1, P3)				
Medium size fish species – adults				
Group AUS1 – Eel-tailed Catfish	adults 15–25 cm	0.45 m/s to 0.75 m/s	0.9 m/s to 1.5 m/s	3 BL/s used for prolonged swim speed (default value)
Group AUS2 – Grunters	adults 15–25 cm			2 x prolonged speed used for burst swim speed (notional value)
Small size fish species – adults				
Group AUS3 – Rainbowfish	adults < 10 cm	0.25 m/s	0.5 m/s	3 BL/s used for prolonged swim speed (default value) 2 x prolonged speed used for burst swim speed (notional value)

Fish movement capability group	Common length of fish	Prolonged speed – nominal	Burst speed – nominal	Comment
JUD – Juvenile upstream dispersal migration (fish movement groups C1, C2, P2, P3, P4)				
Medium – large size fish species – juveniles				
Group JUD1 – Eels	adults 60–100 cm (juveniles to 30 cm)	0.3 m/s to 1.0 m/s	up to 1.4 m/s	Prolonged and burst swim speeds based on data for juvenile eels, barramundi and jungle perch
Group JUD2 – Giant herring/Sea bass	adults 50–120 cm (juveniles to 30 cm)			
Group JUD3 – Flagtails/Herring	adults 20–25 cm (juveniles to 10 cm)			
Small size fish species – juveniles				
Group JUD4 – Hardyheads/misc. species	adults < 20 cm (juveniles to 10 cm)	0.1 m/s to 0.3 m/s	0.2 m/s to 0.6 m/s	3 BL/s used for prolonged swim speed (default value) 2 x prolonged speed used for burst swim speed (notional value)
Group JUD5 – Gobies/Grunters/Gudgeons	adults 10–20 cm (juveniles to 10 cm)			
Group JUD6 – Cardinalfishes/Glass perchlets/Gobies/Gudgeon	adults < 10 cm (juveniles to 5 cm)			

Source: Kapitzke (2006).

2.3.2 SWIMMING BEHAVIOURS

Behavioural and morphometric differences between different fish species have been found to impact on rates of fish passage success in a laboratory environment (Watson et al. 2019). Some key factors include:

- depth station
- preferred habitat
- scale of migration (micro, meso, macro)
- station holding
- rheotactic response.

Depth station refers to the position which the fish inhabits in the water column. Fish which prefer to swim near the stream bed and banks may be weaker swimmers than those which swim higher in the water column since lower velocity conditions can be found near the bed due to boundary layer effects. Preferred habitat may also be an indicator of swimming ability, for example fish which typically inhabit wetlands and other slow flowing habitats may be weaker swimmers than species which spend most of their life cycle in open flowing streams. Scale of migration may also be an indicator of swimming ability, as species which migrate over longer distances are likely to be strong swimmers at the life cycle stage where the long migration is undertaken.

Rheotactic response

Rheotactic response (rheotaxis) is a key biological factor which influences the behaviour of fish when they are swimming either upstream against moving flow or downstream with the current. Positive rheotaxis refers to the tendency of upstream-swimming fish to orientate themselves against the direction of flow, while negative rheotaxis is the opposite, and is observed for some downstream migrators such as eels. Water currents are thought to provide a directional cue for migrating fishes, particularly for diadromous species (Arnold 1974).

Positive rheotaxis is generally the most important factor for fish passage design considerations, as a level of attraction flow is needed at culvert exits, and throughout culverts in order to trigger rheotactic response and

attract fish to swim through the culvert. If the water velocity through a culvert barrel is too low, the rheotactic response of fish may be lessened, and fish may not swim to their full capacity in their efforts to pass the culvert. This is evidenced by the flume swimming performance of certain fish species including *H. klunzingeri* (western carp gudgeon) and *A. agassizii* (Agassiz's Glassfish) which perform poorly in terms of traverse success when swimming in enhanced culvert reduced velocity zones (RVZs) (produced by roughening and longitudinal beam treatments), but show high swimming endurance, indicating that the fish is not swimming strongly enough to tire (email conversation with Dr J. Watson, Mar 2020).

The need for attraction flow at the upstream end of a culvert to facilitate downstream migration linked to negative rheotaxis should also be considered. Where a multi-barrel installation is used, upstream channel treatments may be required to direct downstream migrators into the primary flow channel, or culvert cell.

Station holding

Station holding is an aspect of fish behaviour which is exhibited by many species of small fish, including gudgeons, galaxiids, salmon parr and darter species (Watson et al. 2019). Of these species, gudgeons and galaxiids are most prevalent in Australia (Humphries & Walker 2013). Station holding involves fish using their pectoral fins to grasp the stream substrate, which is thought to allow for conservation of energy when attempting to move against the streamflow (Goodrich et al. 2018).

During their testing for the measure of U_{crit} and U_{sprint} data, Watson et al. (2019) observed station holding behaviour by the species *H. compressa*, *H. galii*, *M. adspersa*, *P. grandiceps* and *R. bicolanus* which are all benthic, i.e. species which prefer to swim near the base of the water column. Station holding was particularly evident when the species were swum at velocities which were not challenging, and when velocities were increased to challenging levels, the fish were unable to maintain their hold on the smooth PVC surface of the experimental channel (Watson et al. 2019).

Use of station holding at greater velocities may be possible in concrete pipe or box culverts and corrugated metal culverts as these materials generally have greater roughness than PVC (Chow 1959). A comparison of Manning's roughness coefficients for common culvert materials compared to PVC is shown in Table 2.4.

Table 2.4: Manning's roughness coefficients (n) for common culvert materials

Material	Manning's n
PVC (experimental setups)	0.009–0.011
Precast concrete	0.010–0.013 (free of debris)
	0.011–0.014 (with some debris)
Corrugated metal	0.021–0.030 (storm drain)

Source: Chow (1959)

The increase in Manning's coefficient when comparing to PVC is fairly marginal for concrete culverts, but more significant for corrugated metal culverts. Station holding capability may potentially be further enhanced by artificial roughening, although it should be noted that this may in fact hinder the swimming ability of some species including *T. tandanus* (eel-tailed catfish), which is widespread throughout coastal Queensland and the Murray-Darling basin (Goodrich et al. 2018). This highlights the importance of considering the natural stream conditions in the vicinity of the culvert when developing a roughening treatment. Ideally, the roughness and velocities within a culvert should be comparable to those within the natural stream under flow conditions where fish are attempting passage.

Artificial roughening leads to an increase in turbulence at bed level, and although *T. Tandanus* is a benthic-swimming fish, it is known to inhabit still pools, which Goodrich et al. (2018) hypothesises may lead to a lesser tolerance to turbulent conditions. The preferred habitat of certain fish may therefore be an indicator of its tolerance to certain hydrological conditions – for example it could be expected that fish which inhabit free-flowing streams would be more likely to take advantage of turbulent conditions. It is important to consider the behaviour of all species which require passage when developing a solution, and it may be necessary to provide a variety of hydrological zones through a culvert.

2.4 CULVERT CONSTRAINTS FOR FISH PASSAGE

Culverts which have not been designed with a focus on providing fish passage are known to pose a range of hydraulic barriers to the movement of fish (O'Connor, Stuart, & Campbell-Beschoner 2017). This is most often linked to the fact that culverts have historically been designed with a focus on hydraulic efficiency and cost minimisation, although there has recently begun to be an increased focus on fish passage functionality (Rodgers et al. 2014). Barriers may exist due to the design or condition of the culvert barrel, culvert apron, or the upstream/downstream approaches to the structure (Kapitzke 2010c). Some key known barriers to fish passage at each hydraulic zone of a culvert are summarised in Table 2.5. The impacts of each of these barriers are summarised in Table 2.6.

Table 2.5: Common barriers to fish passage posed by culverts

Hydraulic zone	Barriers to fish passage
Downstream channel	High velocities, excess turbulence, water surface drop
Culvert outlet and downstream apron	High velocities, shallow water depth, lack of resting place or shelter, excess turbulence, water surface drop
Culvert barrel	High velocities, shallow water depth, lack of resting place or shelter, excess turbulence, inadequate lighting
Culvert inlet and upstream channel	High velocities, shallow water depth, lack of resting place or shelter, excess turbulence, water surface drop

Source: Kapitzke (2010c).

Table 2.6: Impacts on fish passage caused by common barrier effects

Barrier effect	Impact on fish passage
High velocity due to: - steep gradients - uniform channel with lack of roughness - constriction of waterway	Culvert velocities pose a barrier to fish passage when the distance between rest points is greater than the maximum distance fish can swim at burst speeds.
Shallow water depth due to: - steep gradient culverts - wide culvert bases that disperse flow	Shallow water can inhibit fish swimming effectively, particularly larger species. Fish may become injured, especially in high flow conditions.
Lack of resting place or shelter due to: - simplified channel form - lack of substrate complexity	Lack of resting places pose a barrier to upstream fish passage if the length between shelter areas is greater than the maximum distance fish can swim between resting.
Excess turbulence due to: - steep gradient culverts - constriction of water at culvert inlet - upstream build up - low tailwater levels	Turbulence levels may exceed tolerance of particular fish and therefore present a barrier to upstream movement. Fish lose ability to navigate through the culvert and they are unable to recognise primary flow direction.
Excessive head loss due to: sudden change in bed profile	Many Australian native fishes have little capacity to jump and are therefore unable to negotiate small water surface drops.
Low levels of light due to: long, narrow culverts	Many Australian native fishes have a tendency to avoid dark areas and may not enter culverts with reduced light levels relative to the stream outside of the culvert.

Source: O'Connor, Stuart, and Campbell-Beschoner (2017).

Barriers may also result from debris blocking a culvert barrel, which makes frequent inspection and maintenance crucial for fish passage. Certain fish passage designs such as weir baffles may exacerbate the issue of debris by providing a surface for debris to accumulate against (Kapitzke 2010e). Barrel length is a

restrictor if it is longer than the distance that the target fish can swim for at critical speed. Water surface drops at the downstream end of the culvert may arise from scour if bedding materials are unsuitable.

In general, there is limited guidance available which defines the point where a culvert becomes an unacceptably insurmountable barrier for Queensland fish species.

2.4.1 WATER VELOCITY

Civil and hydraulic engineering design targets are typically focused on designing a culvert to maximise hydraulic capacity in order to optimise its ability to pass high ARI flow events (e.g. 50, 100 year) while maintaining a certain road transport level of service (Goodrich et al. 2018). In contrast to this, fish passage design generally needs to consider the flow conditions within the culvert for low ARI events (e.g. 1, 2, 5 year, although there does not appear to have been any significant research into this) as these are the magnitude of events during which fish are most likely to attempt passage (Franklin et al. 2018). The exact magnitudes of events when fish are attempting passage are not well-defined however, and it is likely that the events that need to be considered for fish passage design will vary depending on catchment hydrology and the characteristics of the fish attempting migration. Discharge magnitude varies during a typical rainfall-induced flow event as discussed in Section 2.2.3, and water velocity varies in turn during an event, which means that a culvert may not act as a barrier at all times during a flow event.

The Queensland Accepted Development Requirements (ADR) for waterway barrier works do not explicitly define a minimum culvert flow velocity which can be used in all situations, but for red mapped waterways (high importance fish habitat) it is stated that:

Roughening elements aim to achieve a contiguous lower velocity zone (no greater than 0.3 m/sec) for at least 100 mm width from the wall through the length of the culvert.

There is no definitive guidance provided relating to the range of discharge conditions for which this contiguous velocity must be achieved, but the overarching SDAP code specifies that (Queensland Department of Infrastructure, Local Government and Planning 2017):

Hydraulic conditions (depth, velocities and turbulence) from the downstream to the upstream limit of the structure allow for **fish** passage of all **fish** attempting to move through the crossing at all flows up to the **drownout** of the structure.

This statement stipulates that fish passage conditions must be provided for during all flow conditions up to culvert drownout providing that there are fish attempting passage at all flow conditions up to drownout, with the assumption being that fish will be able to gain passage over the top of the culvert structure once drownout occurs. This has led to the general requirement that a 0.3 m/s contiguous low velocity zone is provided for all culvert flows up to drownout. This requirement has significant cost and engineering implications for structures. Where modification works to existing structures is occurring, it may not be practicable to achieve this condition without adverse impacts to afflux or the road asset.

The 0.3 m/s maximum velocity specified by Queensland Department of Agriculture and Fisheries (2018) corresponds to that recommended by the NSW *Fish Passage Requirements for Waterway Crossings* for water depths up to 0.5 m in smooth bedded culverts (Fairfull & Witheridge 2003). The 0.3 m/s (with an additional specification of < 10 mm head loss) is also specified by the Victorian *Guidelines for Fish Passage at Small Structures* (O'Connor, Stuart, & Campbell-Beschorner 2017), but there is no guidance provided relating to discharge conditions for which this must be achieved, or the percentage of culvert area that the velocity must be achieved over. It could be cautiously assumed that the figure of 0.3 m/s specified by the NSW fish passage requirements and the Victorian fish passage guidelines is intended to refer to average cell velocity. This may be excessive, considering that research has shown that fish will target reduced velocity zones when attempting passage (discussed in the following section).

The maximum velocity figure of 0.3 m/s was originally determined for Australia based on research conducted by Mallen-Cooper (1999b) which is discussed in Section 2.3.1. It has been postulated by some that this velocity may not be applicable for the passage of all Australian fish species (Goodrich et al. 2018). Further research has been conducted with the aim of identifying the swimming ability of small-bodied species.

Consultation with a practicing fish biologist indicated that there is not currently a great volume of research supporting the figure of 0.3 m/s based on fish ability, but there is also not sufficient research to disprove the figure (phone conversation with T. Marsden, Feb 2020).

Gordos et al. (2007) conducted a review of waterway barriers to fish passage in NSW. They found that excessive water velocity through box culverts was not often observed, but excessive velocities were a significantly greater problem for pipe culverts. Gordos et al. (2007) classify 'excessive' velocities to those in excess of 0.3 m/s for water depths up to 0.5 m which is the recommended limit in NSW where fish passage is required (Fairfull & Witheridge 2003), but this is not explicitly defined.

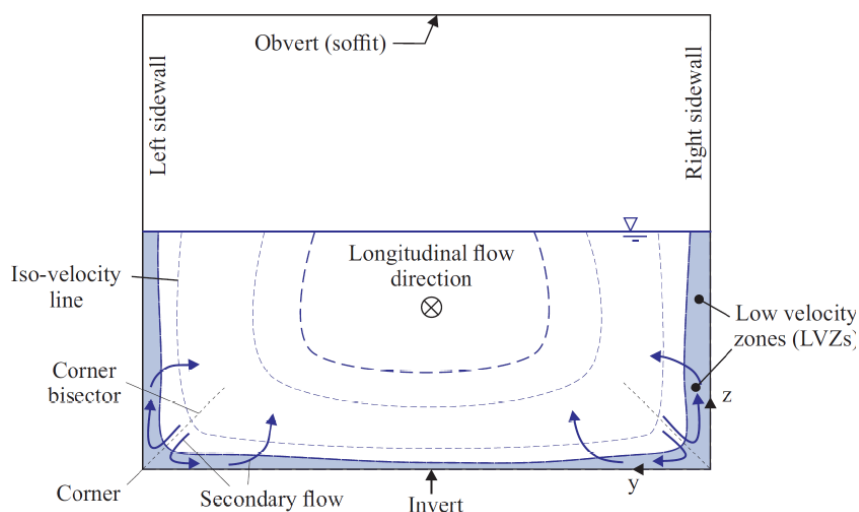
Flow through culverts which are constructed from smooth concrete or steel will usually be homogenous, which is in contrast to the often-heterogenous conditions that are predominant in typical natural waterways (Goodrich et al. 2018). Smooth culverts will also reduce the thickness of the low-velocity boundary layer which forms when liquid flows along a solid surface. This boundary layer is utilised by certain fishes which use it to gain passage against the relatively higher stream velocities away from the boundary layer. Culverts with relatively low flow depths may bar passage to these fishes, and water depth as a fish passage barrier is discussed further in Section 2.4.3. The area of flow which is influenced by the boundary layer effect within a culvert is generally termed the reduced velocity zone (RVZ) when discussing its application to fish passage engineering.

Roughening of culvert inverts results in breakup of homogeneous flow and an increase in the size of the boundary layer. Studies have shown that this is not necessarily beneficial for all fish species, and the ability of any one species to take advantage of surface roughening is likely dependent on its swimming mode, morphology and ecological traits (Goodrich et al. 2018). Bed roughening using river stones was proposed by Goodrich et al. (2018), but this is not necessarily the only possible technique, and the general objective needs to be to generate conditions which are supportive of fish passage outcomes.

Reduced velocity zones (RVZs)

RVZs (also known as Low Velocity Zones (LVZs)) are zones within a culvert barrel which have a lower velocity than the bulk culvert velocity due to hydraulic effects associated with boundary layer formation. These low velocity regions occur along the wetted perimeter of the walls and base of the culvert and are most prevalent in the corners of box culverts where the boundary layers created by the wall and invert of the culvert meet under full-width flow conditions (Figure 2.5) (Chanson & Leng 2019; Goodrich et al. 2018 and Watson et al. 2018). RVZs are also located around the edges of the wetted perimeter in pipe culverts, although the region of reduced velocity is typically smaller than what is generated in box culverts.

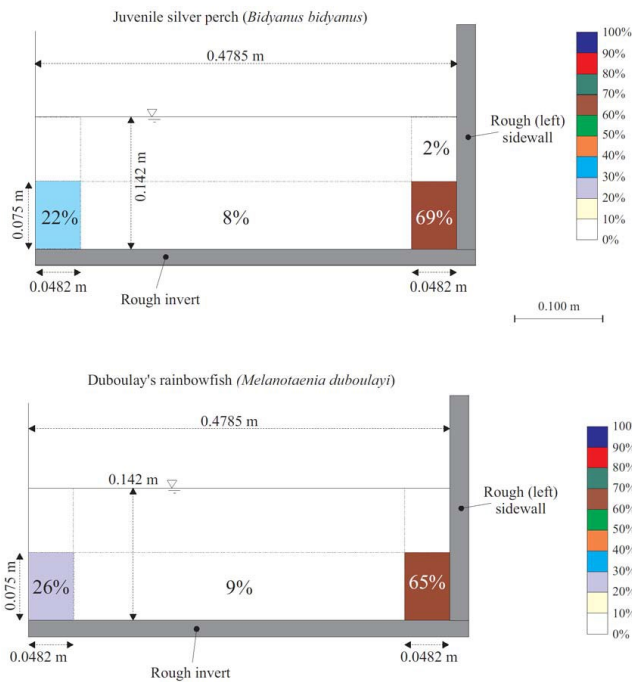
Figure 2.5 Box culvert RVZs/LVZs



Source: Chanson and Leng (2019).

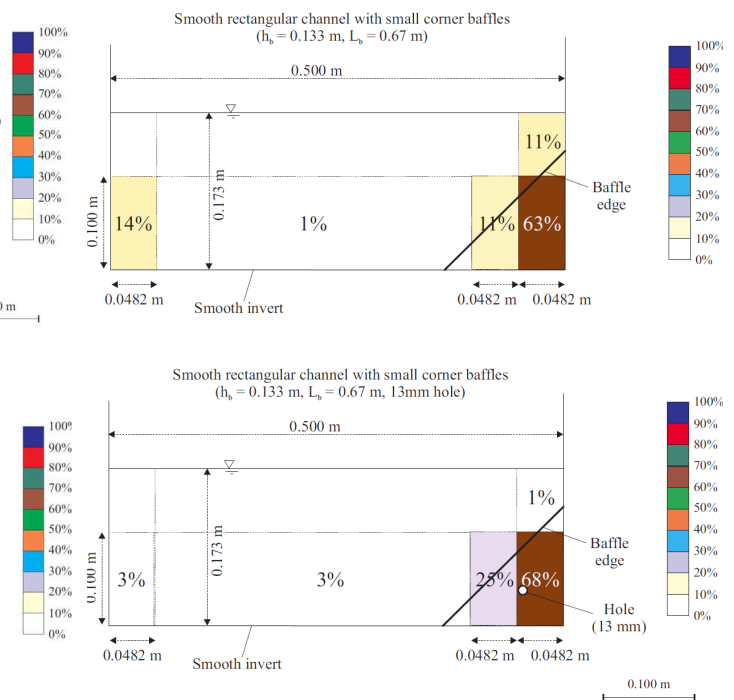
The effect of RVZs is due to the no-slip condition in fluid mechanics, which results in a water velocity of zero at all points of contact with the culvert surface. The water velocity increases as distance from the surface increases, meaning that the most advantageous position for fish to gain passage is near the culvert surface. Some researchers have shown that small-bodied fish will utilise these RVZs in order to gain passage against prohibitive bulk channel velocities (Chanson & Leng 2019; Goodrich et al. 2018, Leng et al. 2019). The proportions of time that fish spent swimming in zones of a box-shaped flume are illustrated in Figure 2.6 and Figure 2.7.

Figure 2.6 Proportion of time spent swimming in each zone – rough sidewall only



Source: Chanson and Leng (2019).

Figure 2.7 Proportion of time spent swimming in each zone – rough sidewall and corner baffle



Source: Chanson and Leng (2019).

In order to allow for successful fish passage, the size of the RVZ must be sufficient to encompass the size of the fishes which will rely on it to gain passage (Chanson & Leng 2019). This may be considered as a relative percentage of the full culvert flow area. Leng et al. (2019) investigated the theoretical design of box culverts for a target percentage (15%) of flow area for which contiguous velocity is below certain characteristic fish swimming speeds.

The research found that the overall cross-sectional area of flow that is required to achieve a target RVZ percentage of 15% of flow area increases as the target flow velocity within the RVZ decreases. Therefore, to cater for weaker fish species, larger culvert arrays will be required to provide the suitable RVZ. Critically, the number of cells required becomes prohibitive if a characteristic swimming speed of less than 0.3 m/s is required to be catered for, and Leng et al. (2019) note that fish passage design for such fish may need to incorporate elements such as baffles or resting areas. This methodology is also highly reliant on tailwater effects. This is not realistic in the majority of culvert situations and therefore limits the applicability of this design methodology.

To achieve fish passage through a culvert, the contiguous velocity within the RVZ should not exceed the critical swimming speed of the target fish species at the developmental stage when it will require passage. The time that the fish will take to achieve successful passage against the RVZ velocity should be considered compared to the length of time that a target fish could be expected to maintain critical speed. If the length of the culvert exceeds the distance that the fish can travel against the culvert velocity, fish will tire before achieving passage, and will be washed downstream if they cannot station hold or rest within an area of lower velocity compared to the contiguous RVZ.

Remediation options

There are a variety of methods which may be used to either adjust flow velocities within an existing culvert or be incorporated into a new design in order to achieve some target flow conditions. These can include (Goodrich et al. 2018; O'Connor, Stuart, & Campbell-Beschorner 2017; Watson et al. 2018):

- increasing flow area to reduce water velocity
- installation of baffles, ropes, other roughening elements to create low velocity resting areas
- bed roughening to increase the size of the low velocity boundary layer and reduce velocities near the culvert invert
- installation of longitudinal beams to enhance reduced velocity zones (RVZs) for contiguous passage
- downstream weir (tailwater) pools which cause water to back up through the culvert and reduce water velocity during targeted flow conditions (induce subcritical flow conditions through culvert)
- countersinking/embedment of new culverts or provision of natural substrate through culvert base
- stream simulation design.

There have been several studies which have investigated options for fish passage through pipe culverts, but there appears to be very limited data available related to the passage of specific Queensland fish species through pipe culverts. There is some value however in considering passage results for other fish species, particularly small bodied fish, as work by Watson et al. (2019) has shown that fish body length is a good predictor of swimming ability.

Wall roughening via baffles

Over the past two decades there has been a multitude of remediation options suggested for enhancing the RVZ along the walls or inverts of culverts. These are generally termed baffles. Baffles are generally accepted by both fish biologists and engineers as the primary remediation method for culverts in order to achieve successful fish passage. A baffle separation distance of four times the width of the baffle is generally accepted as the design standard to ensure a contiguous RVZ, which is based on limited research outcomes.

Research conducted in laboratory flumes has shown that the placement of baffles in the corners or on culvert sidewalls can lead to the impedence of fish which are attempting to use the RVZ to achieve passage of the structure (Watson et al. 2018). This is somewhat in contrast to the findings of Cabonce, Wang & Chanson (2018) who explored the placement of small triangular baffles in the corner of an experimental rectangular flume (Figure 2.7). Cabonce, Wang and Chanson (2018) designed triangular baffles while considering that the baffle size needs to be comparable to the size of the fish that will be attempting passage, and that strong flow reversal, or turbulence must be avoided. It was found that the flow reversal created by solid baffles resulted in the disorientation of some tested fish, but this impact was reduced by introducing a hole in the baffle which allowed for some water flow through it, reducing the turbulent intensity behind the baffle.

Cabonce, Wang and Chanson (2018) found that the baffles substantially improved the passage outcomes of the fish tested, but it should be noted that the species and size classes tested were quite limited. Since the size of the baffle must be well-matched to the size of the fish that will be attempting passage it is likely that this type of baffle treatment would need to be highly targeted and may not be appropriate as a sole treatment where a wide range of species and size classes are attempting passage.

The corrugations in steel pipe culverts are known to produce increased surface roughness and boundary layer effects which reduce near-surface velocities compared to those which would exist in similar sized culverts built using smooth concrete and plastic materials (Behlke et al. 1991). RVZs in pipe culverts are located around the edges of the wetted diameter, and small bodied fish have been observed to take advantage of these zones to gain passage (phone conversation with T. Marsden, Feb 2020). The use of these RVZs by Queensland species, however, does not appear to have been comprehensively studied.

Baffles aim to create low velocity resting areas for fish and break up the flow within culverts in order to reduce velocities in the vicinity of the baffle edge and between individual baffles (Kapitzke 2010e). In order to

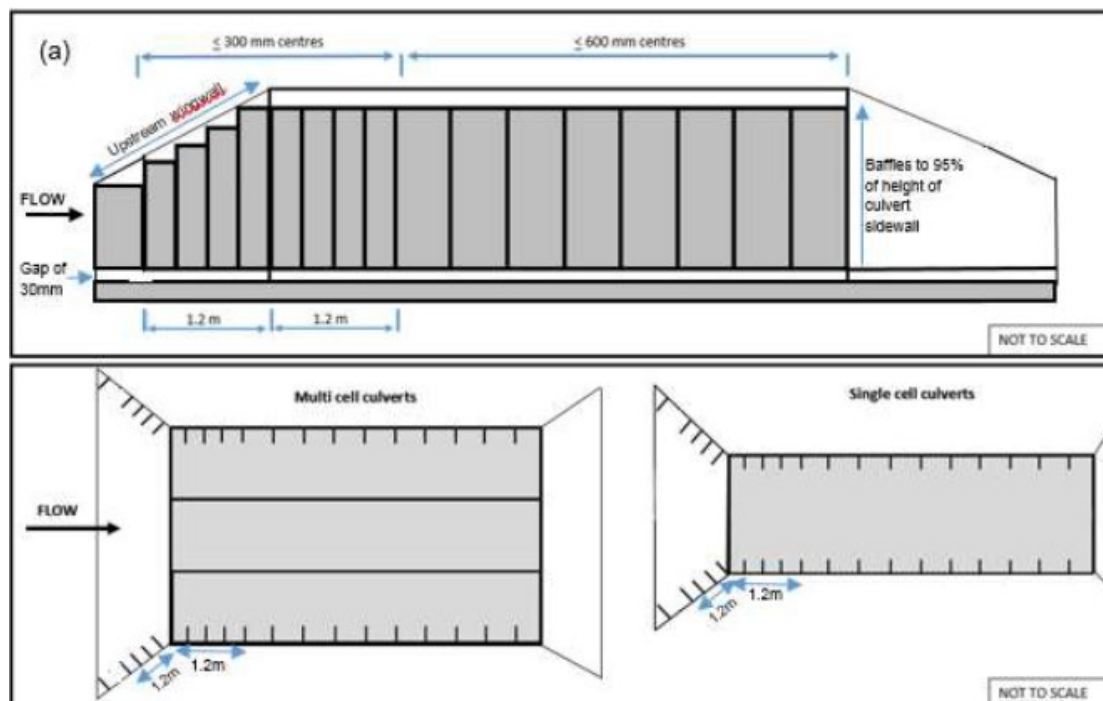
pass a baffled culvert, fish must typically employ a burst and rest approach to swimming, which involves short periods of travel at sprint speed accompanied by periods of rest at cruising speed in low velocity zones created adjacent to the culvert wall in between baffles. Refer to Section 2.3.1 for discussion of fish swimming mechanisms.

The current baffle configuration prescribed by the Queensland Accepted Development Requirements (ADR) is as follows:

- maximum 150 mm horizontal protrusion (width) into the flow
- maximum 10 mm thick (leading edge)
- within 1.2 m upstream and downstream of the upstream culvert inlet, baffles must be spaced at twice the horizontal protrusion (width) of the baffle (i.e. maximum 300 mm centres)
- throughout the rest of the structure, baffles must be spaced at 4 x horizontal protrusion (width) of the baffle (i.e. maximum 600 mm centres).

The ADR baffle configuration is illustrated in Figure 2.8, Figure 2.9 and Figure 2.10.

Figure 2.8 ADR baffle configuration



Source: Queensland Department of Agriculture and Fisheries (2018)

Figure 2.9 ADR baffle detail

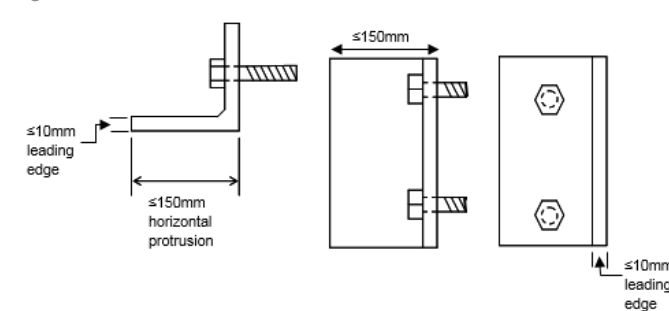
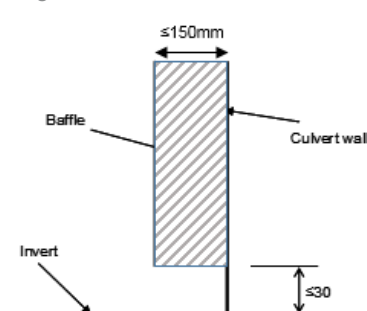


Figure 2.10 ADR baffle section



Source: Queensland Department of Agriculture and Fisheries (2018)

It is unclear what degree of modelling or field assessment this baffle configuration has been predicated on, but successful passage of small fish in culverts which include the baffles has been observed during high discharge conditions (phone conversation with T. Marsden 2020). To date, this observed passage has not been formally quantified in terms of passage numbers or success rates. Some visual evidence of high numbers of empire gudgeons (20–40 mm fish length range) moving against a flow of 0.75 m/s was observed in a 4 m long experimental culvert flume setup located on the O’Connell River in the Mackay-Whitsunday region which was fitted with an experimental baffle system similar to the prescribed configuration (Marsden 2015). The baffles were observed to improve passage success by up to 40% compared to a non-baffled control setting, but it must be recognised that the 4 m length of the experimental flume is significantly shorter than a typical road culvert. It is unclear whether similar passage success results could be expected for a longer culvert, and it is possible that passage success may reduce.

In contrast to this observation, ongoing research being conducted by UQ has shown that the current baffle configuration may hinder the passage of some native species of small-bodied fish, since the presence of the baffles precludes the formation of an RVZ in the bottom corners of box culverts where they are installed (refer to discussion on Reduced Velocity Zones (RVZs) in a subsection of Section 2.4.1) (phone conversation with Dr J. Watson, Jan 2020). Laboratory swim trials have shown that the turbulent vortexes created downstream of the baffles can result in smaller bodied fish becoming disorientated and being washed downstream (Watson et al. 2018). It is noted that laboratory trials can produce overly conservative results with regard to fish capability, which can be due to a range of factors including the use of captive-bred fish, hard-to-quantify behaviours such as station holding or differences between lab and field conditions (Watson et al. 2019), which may in part explain the observed passage outcomes in the field.

A range of baffle options for pipe culverts is described by Kapitzke (2010e), include offset baffle (Figure 2.11) and corner ‘quad’ baffle (Figure 2.12) fishway designs. They note that the offset baffle is a relatively old design, having historically been used extensively within box and pipe culverts in the northern hemisphere, but has lost favour in recent decades being replaced by designs such as the spoiler baffle or weir fishway (Kapitzke 2010e). An experimental culvert baffle setup was established at the site of an existing pipe culvert situated within University Creek by researchers from James Cook University in Townsville. The culvert consisted of four-cells, and the experimental baffle fishways were installed on two adjacent cells (offset baffle in one cell and corner ‘quad’ baffles in the other cell).

The baffle designs implemented by Kapitzke (2010e) had some degree of success, but this has not been comprehensively quantified. Biological monitoring of the experimental culvert baffle setups was performed by means of visual observations and fish trapping techniques. Monitoring showed that there were six native species captured or observed on the upstream and downstream sides of the baffled culvert. This contrasts with no detections of native fish species upstream of the culvert prior to the installation of the baffle fishway. This indicated that there was some degree of successful passage through the culvert, but this was not formally quantified, and it is unclear what discharges were experienced during the observations prior to baffle installation.

Figure 2.11 Offset baffles



Source: Kapitzke (2010e).

Figure 2.12 Corner 'quad' baffles



Source: Kapitzke (2010e).

Spoiler baffles are another option used primarily for pipe culverts where concrete or moulded plastic blocks are placed in an intermittent pattern along the base of a culvert. These are recommended for use in NZ (see Section 2.5.5), and have been implemented and monitored on a southern Tasmanian pipe culvert (MacDonald & Davies 2007). The species monitored in the Tasmanian study were common galaxias (jollytail) and spotted galaxias, which are not widespread in Queensland (limited to SE corner). Passage trials were conducted at water flow velocities of 0.35, 0.70 and 1.0 m/s based on swimming ability data for the galaxias species in literature. Fish were observed to use a burst and rest swimming pattern to gain passage through the baffled culvert, and the fish tested were at least 10 times more likely to gain passage through the baffled culvert when compared to a control culvert, although passage success was relatively lower at the higher velocities for both the baffled and control culverts.

There are currently a range of baffle designs proposed for both box and pipe culverts, and development of further design options is ongoing (Witheridge 2020). Generally, the literature shows agreement that baffles will improve fish passage outcomes, but this has not been comprehensively quantified for most designs, including the current baffle solution prescribed by the Queensland ADR. Field monitoring of baffle options during flows when fish expected to be attempting passage is required to comprehensively assess baffle effectiveness and impact on fish populations.

Longitudinal beams

An alternative wall treatment to the wall baffle is the concept of longitudinal beams that run along the walls of a culvert. Longitudinal beams are a relatively new and yet to be field-tested treatment concept which is being investigated by the University of Queensland through a range of laboratory swim trials. Longitudinal beams are designed to enhance the RVZ which is generated in the corners of box culverts where the wall and invert meet. This treatment is best suited for the passage of smaller fish and is intended to produce a consistent zone of reduced velocity for the full length of a retrofitted culvert (Watson et al. 2018). Positioning and size of suggested longitudinal beams are shown in Figure 2.13 and Figure 2.14.

Recent yet-to-be published research by the University of Queensland has shown that the longitudinal beams treatment has varying rates of success for different species of small-bodied fish and juveniles of larger-bodied species (email conversation with J. Watson, Jan 2020). They state that these varying results are most likely due to the different swimming abilities of each species, and the effects of rheotactic response. The longitudinal beams treatment is not intended to assist the passage of larger bodied fish, and it is noted that alternative treatments may be used in conjunction with the beams in order to meet the requirements of these fish (Watson et al. 2018).

The introduction of culvert bed roughening in addition to the beam treatment increases traverse success rates for certain species, in particular those species which use the roughened substrate to station hold and rest while attempting passage (email conversation with J. Watson, March 2020). Traverse success increased

from 13% to 24% for the western carp gudgeon (*H. klunzingeri*) with the addition of roughening in one set of trials. As noted in previous discussion, bed roughening may be detrimental to species which prefer less turbulent conditions at bed level (Goodrich et al. 2018), although provision of natural substrate matching the stream bed may be a preferable option.

Figure 2.13 Single longitudinal beam treatment

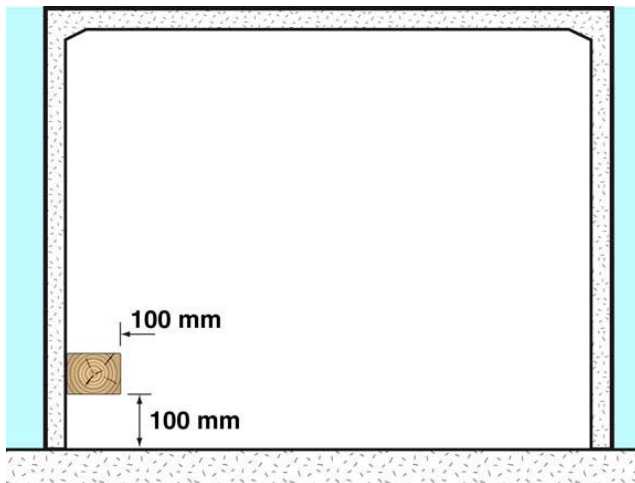
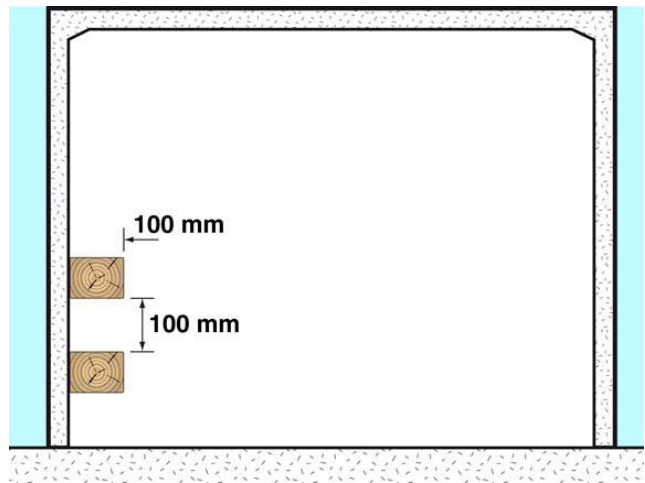


Figure 2.14 Stacking of multiple longitudinal beams



Source: Witheridge (2020).

Tailwater weir

Tailwater weirs are installed downstream of culverts and are intended to create a pool at the downstream end of a culvert and back a certain depth of water up through culverts during fish passage flows. This can be used to increase water depths and reduce velocities through culverts, and/or overcome hydraulic jumps at outlets (Amtstaetter et al. 2017; California Department of Transportation 2014; O'Connor, Stuart, & Campbell-Beschorner 2017). In order to effectively augment fish passage, tailwater weirs can be combined with a rock ramp fishway (or other fishway) to facilitate passage of fish over the weir (Amtstaetter et al. 2017).

A combination of a concrete fixed crest weir and rock ramp fishway was installed 10 m downstream of a 70 m pipe culvert located on Cardinia Creek in southern Victoria to enhance fish passage outcomes. This culvert was experiencing an average cell velocity of 0.9 m/s at moderate discharges (50 ML/d) which exceeds the acceptable velocity for fish passage of small-bodied species (0.3 m/s). The fishway installed consisted of three rock ridges which resulted in the creation of three 5.8 m wide by 2.0 m long pools (meaning installation extends at least 16 m from the culvert outlet). Six stainless steel baffles were added to the upstream end of the culvert to break up laminar flow as the long length of the structure resulted in water not being backed up over the full length (Amtstaetter et al. 2017).

Figure 2.15 Cardinia Creek rock ramp fishway (L) and pipe culvert baffles (R)



Source: *Amtstaetter et al. (2017)*.

The effectiveness of the tailwater weir and rock ramp treatment was investigated through capture and release of tagged fishes at the target site and a downstream control site, the majority of which were common galaxias. It was found that passage through the culvert increased following the installation of the treatments, with a combined total 6 fish passing the culvert from five pre-treatment tests, and a combined total of 106 fish (99 common galaxias, five spotted galaxias and two climbing galaxias) passing the culvert from five post-treatment tests. This corresponded to average 3% passage probability pre-treatment, and an average 41% probability post-treatment.

It was also found that the proportion of marked fish that achieved passage through the modified culvert site increased with higher discharges, which seems to indicate that the treatment is more effective at higher flows. Success rates across the five post-treatment tests ranged from 7% at a discharge of 10.2 ML/d (number of fish = 41) to 59% at a discharge of 12.6 ML/d (number of fish = 65), and 58% at a discharge of 16.4 ML/d (number of fish = 60). The velocity conditions within the culvert for each of these discharges are not specified, but it is stated that the treatment is intended to produce zero velocity through the culvert at low flows, which may be detrimental to fish passage if insufficient attraction flow is being provided to induce fish to swim through the culvert (O'Connor, Stuart & Jones 2017). This highlights the importance of considering low flow conditions in fish passage design.

Amtstaetter et al. (2017) is the only Australian example to date that has conducted a formal study on the performance outcomes associated with installing a tailwater weir and rock ramp fishway downstream of a culvert to improve fish passage. Rock ramp fishways for culvert fish passage have been installed in Queensland in the past, with one such example installed to improve passage outcomes through a box culvert on Kirknie Creek in the Burdekin catchment (Queensland Department of Agriculture, Fisheries and Forestry 2014). It is unclear whether any formal monitoring of this installation was completed. The use of tailwater weirs to improve conditions for fish passage appears to be an accepted method in the USA, being included in some state guidelines (Caltrans 2014).

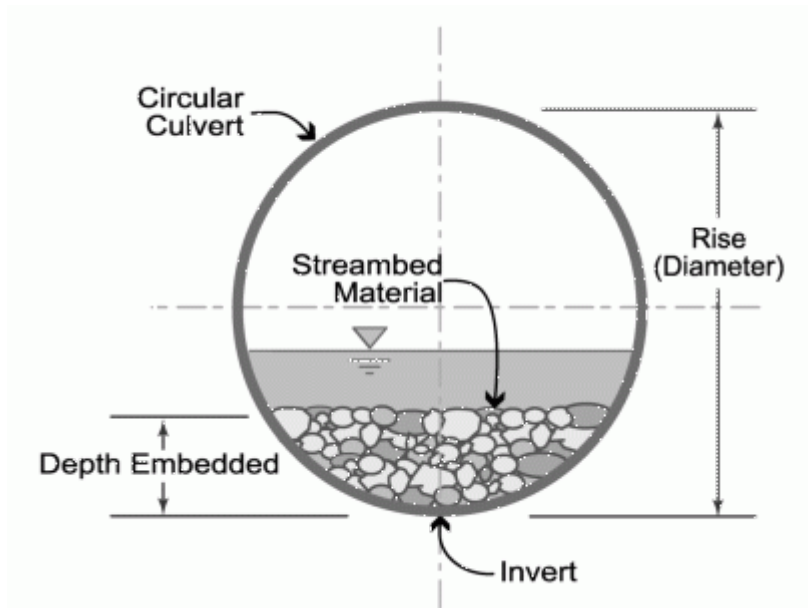
A key issue cited by TMR regarding rock ramp fishways was that treatments will typically need to fit within the road reserve, which may not be possible for conventional fishway installations. The positioning of the fence in the background of Figure 2.15 appears to indicate that the fishway was installed within the road reserve, but it is unclear what reserve width existed for the site, or whether any arrangements were made with a private landowner or other agencies.

Countersunken culverts (embedment)

Countersinking refers to the practice of burying culvert barrels to a certain depth below the natural stream bed so as to maintain the natural stream bed throughout the length of the barrel (Figure 2.16). This enhances the boundary layer (RVZ) at bed level, and creates reduced barrel velocities at bed level compared to standard culverts, although there will still typically be some constriction of the stream width which may result in higher velocities relative to the open stream velocity. The increase in surface roughness with natural bed compared to smooth concrete results in greater friction along the surface which in turn increases the width of the RVZ.

The countersinking of culverts is currently required in Queensland for culverts on major and high-risk waterways for waterway barrier works as mapped by DAF. Concerns with countersunken culverts from an engineering perspective are that the base and lower walls of the culvert are often covered by bed substrate. This makes regular engineering integrity inspections very difficult and expensive.

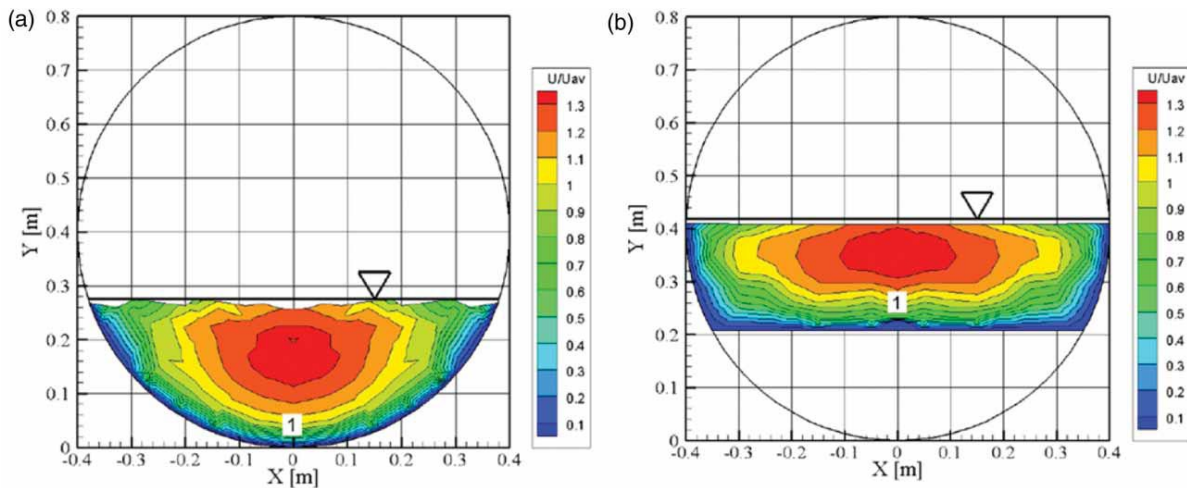
Figure 2.16 Countersunken pipe culvert example schematic



Source: *The FishXing Team (2004)*.

Physical modelling of in-barrel culvert velocity distributions by Clark, Toews and Tkach (2014) showed that countersinking of steel pipe culverts resulted in a velocity distribution within the pipe similar to that of a rectangular culvert section, which is considered to be hydraulically more friendly for fish passage (Briggs & Galarowicz 2013; Wang & Chanson 2018). The velocity distributions measured by Clark, Toews and Tkach (2014) for a 21 m long, 0.8 m diameter corrugated metal pipe are shown in Figure 2.17, and it can be seen that there are low velocity regions located in the corners of the embedded cross-section, and narrower low velocity regions located at the edges of the fully circular cross-section.

Figure 2.17 Velocity distribution for (a) non-embedded fully developed flow and (b) fully developed flow with 30% embedment



Source: Clark, Toews & Tkach (2014).

Leng et al. (2019) undertook computational fluid dynamics (CFD) calculation for a box culvert barrel invert buried 0.3 m below natural ground level in line with current NSW fish passage guidelines (Fairfull & Witheridge 2003). They found that the provision of a pool of water below bed level resulted in more complex hydrodynamic conditions and an increase in the relative area of culvert barrel for which velocity fell below 0.3 m/s at flow magnitudes below the design flow event (which was set as a 1 year ARI). It is unclear whether natural substrate was considered when undertaking CFD analysis for the recessed culvert. It could also be considered unlikely that a pool with dimensions equal to the length of the culvert multiplied by the depth of embedment would be maintained in a culvert under field conditions, unless the stream was non-alluvial and significant sediment transport was not occurring. Furthermore, it is unclear whether the provision of a pool of water within a culvert under low flow conditions is the intention of installing culverts below bed level as specified by the NSW fish passage guidelines. Also this raises potential concerns for standing water in culverts.

When designing an embedded culvert, it is important to ensure that the shear forces generated by flow through the culvert do not exceed the resistance of the substrate, otherwise excessive scour and displacement of substrate will occur (Franklin et al. 2018). There are various design methods which can be applied to determining expected sediment travel under various flow conditions (Hotchkiss & Frei 2007). Certain stream bed types such as sand and medium gravel will undergo continual substrate and sediment movement under most flow conditions, but significant scouring should not occur as substrate which is displaced from the culvert bed should be replaced by incoming flows (Hotchkiss & Frei 2007). For streams with clayey substrate or similar where significant movement of substrate does not occur, materials such as rounded stone can be grouted to the culvert bed in order to produce roughness (Fairfull & Witheridge 2003).

The current guidelines for culvert fish passage design in Queensland and other Australian states do not appear to provide guidance relating to effective culvert embedment beyond specification for a minimum embedment depth and the provision of erosion protection upstream and downstream of the structure. This erosion protection is important for embedded structures to ensure that erosion of the stream bed and creation of a vertical drop (head cut) does not occur upstream of the structure, but it may not prevent the scouring of bed material from within the culvert barrel if velocities within the barrel exceed bed material resistance. Scouring is a particular issue at discharges below which substrate transport from the natural stream is able to achieve replenishment of displaced substrate. If scouring of natural material from within the culvert does occur, the velocities within the barrel will increase, and natural resting areas for fish attempting passage will be reduced. Scouring also has the potential to create a vertical drop of up to 300 mm at the inlet of a culvert, which is a barrier for fish passage (see Section 2.4.5).

Stream simulation design

Stream simulation is an approach to culvert design which aims to recreate natural stream conditions as closely as possible within the target culvert. The design philosophy is predicated on the premise that recreating natural stream conditions within a structure will mean that the structure will present no more of an obstacle to aquatic fauna movement than the adjoining channel (US Department of Agriculture 2008). Practically, stream simulation typically involves:

- some form of culvert embedment
- use of open-bottomed structures (arches)
- provision of natural substrate through the culvert.

For stream simulation to be successful, the culvert installed should have a span greater than the bankfull width of the stream in which the culvert is installed (Hotchkiss & Frei 2007). This maintains culvert barrel velocities at levels similar to stream velocity and prevents the excessive scouring of material from within the culvert.

Culvert embedment is recommended in most Australian design guidelines, although stream simulation design is not explicitly referenced. US Department of Agriculture (2008) provides extensive stream simulation design advice for application to culvert design in the USA, although most of the principles presented are relevant in all jurisdictions as stream simulation does not target specific fish or other species for passage outcomes. Culvert embedment by itself should not be considered stream simulation design if full stream simulation design considerations are not followed. Stream simulation design is inherently multidisciplinary and will generally require input from experts in aquatic biology, fluvial geomorphology and hydraulic engineering. Stream simulation design is recommended as best practice by the NZ guidelines for structures up to 4 m, but hydraulic design (i.e. matching hydraulic conditions within a culvert to swimming capability of target fish species) is also allowed where stream simulation design is unreasonable, or for the rehabilitation of existing culverts (Franklin et al. 2018).

Since the width of the primary culvert cell must exceed stream bankfull width, installations which consist of multiple pipes or boxes to span bankfull width do not meet stream simulation design criteria (US Department of Agriculture 2008). The NZ fish passage guidelines also state that multi-barrel culverts should be avoided when unimpeded fish passage is required, since velocities within the individual barrels will be increased relative to the natural stream conditions (Franklin et al. 2018). Large corrugated metal or concrete open-bottomed arch culverts or partially embedded pipes are the most common options for stream simulation culverts shown by US guidelines for stream simulation design (US Department of Agriculture 2008).

The need to provide large width culverts for stream simulation design will result in higher capital costs in some cases, but ongoing maintenance costs will likely be lower than for a traditional culvert since accumulation of obstructing debris and scouring of bed material should be minimised if culverts are designed correctly (Franklin et al. 2018; US Department of Agriculture 2008). Stream simulation design also does not require the swimming ability of migrating fish to be considered, as the aim is to recreate natural stream conditions which should theoretically allow passage for all fish which are attempting it (Franklin et al. 2018). Stream simulation design has reportedly been applied for culverts installed on up to a 15% gradient but has not been used extensively for low gradient streams in fine sediments, cohesive soils or densely vegetated streambeds (US Department of Agriculture 2008).

Stream simulation is also constrained by the topography and vertical alignment of the road. In western Queensland the wide, shallow waterway bed and banks makes stream simulation difficult.

Figure 2.18 Stream simulation design best practice



Source: Franklin et al. (2018).

Mussel spat ropes

These are a novel solution (shown in Figure 2.19) which have primarily been developed in New Zealand with the aim of providing a cost-effective option for enhancing passage of small bodied fish (David et al. 2014; Franklin et al. 2018). The ropes have been tested in a 350 mm diameter laboratory pipe culvert setup with a maximum length of 6 m, which is quite short compared to typical culvert lengths which might be found in Queensland (typically 8 m or greater in length) (David et al. 2014). Common galaxias and juvenile brown trout (salmonid) were tested in addition to freshwater shrimp which is a climbing species.

It was found that the ropes improved passage success for the common galaxias for both flow conditions tested (0.24 L/s and 0.75 L/s), although passage success was low at the highest flow setting (16% for common galaxias). Where common galaxias could not pass the culvert at sprint speed they were observed to 'burrow' into the rope and station hold, which the juvenile trout did not do, resulting in greater passage success by the galaxias compared to the salmonid trout at higher flow rates.

Mussel spat ropes have reportedly been used to enhance passage of eels at sites in Australia (phone conversation with T. Marsden, Feb 2020). No formal testing of the ropes has been undertaken with Queensland fish species. The ropes may be a cost-effective option for enhancing passage outcomes in pipe culverts, but their range of applicability may be limited depending on the swimming behaviour of target fish and culvert length. The ropes will also likely be unsuitable for use by larger bodied fishes. Issues have been reported in NZ relating to ropes being stolen which highlights the need to consider potential vandalism when selecting a fish passage solution (Franklin et al. 2018).

Figure 2.19 Recommended mussel spat rope installation in NZ pipe culvert



Source: Franklin et al. (2018).

2.4.2 TURBULENCE

Excessive turbulence may result from waterways/culverts with steep gradients, sudden changes in bed profile and/or waterway area, or low tailwater levels. It may also result from features within a culvert such as corners, walls, blocks or accumulated debris. Turbulence can cause fish to lose their orientation and become unable to identify the upstream travel direction within a culvert (Kapitzke 2010c). Contrary to this, some species and/or size classes of fish can utilise turbulence as a ‘boost’ to swimming ability in order to conserve energy, which has been investigated in several studies (Chanson & Leng 2019).

The interaction between small-bodied fish and turbulence within an experimental culvert setup was studied by Chanson and Leng (2019). The size, body type and methods of swimming utilised by a given fish species contribute to a fish’s ability to take advantage of turbulent conditions. The size of turbulent eddies must be well matched to the length of the fish for passage benefits to be realised, otherwise turbulence may be detrimental as fish will need to fight against the turbulence to move upstream (Chanson & Leng 2019; Wang & Chanson 2018).

Bed roughening and the installation of baffles are treatment options which can be effective for the treatment of excessive velocities within culverts. These remediation options by nature create turbulent flow, which can be beneficial for some species and size classes of fish, but detrimental for others. Some fishes are able to derive a swimming performance benefit from turbulent flow by utilising eddies to propel themselves forward against the direction of flow (Chanson & Leng 2019; Watson et al. 2018), but the size of the eddies must be comparable to the size of the fish attempting passage for the best results to be realised. Some other species of fish are unable to utilise turbulence, and may become disorientated and fail to complete passage (Watson et al. 2018). The intensity of turbulence varies according to changes in velocity, and it may be the case that favourable turbulent conditions for different species and fish sizes are created at different times during a flow event as discharge and velocity vary, but this would be hard to quantify.

Key to the success of any artificial roughening treatment is understanding how the created flow conditions within the culvert compare to the natural stream bed conditions in terms of flow velocity, turbulence, and boundary layer configuration. It stands to reason that flow conditions similar to those which exist in the natural waterway will have the greatest benefit for species which are attempting passage.

Goodrich et al. (2018) studied the benefit of applied bed roughening in the form of pebbly substrate for four species of small-bodied or juvenile Australian fish. They found that within the experimental setup, bed roughening was beneficial for two of the species studied (crimson spotted rainbowfish and Murray cod), but

detrimental for the eel-tailed catfish and ineffectual for the empire gudgeon. The eel-tailed catfish is known to inhabit still pools, which may explain its low tolerance for turbulent conditions near the channel bed.

2.4.3 WATER DEPTH

Providing sufficient water depth through a culvert during flows when fish are attempting passage is critical to successful passage. Without sufficient water depth, fish may tire more quickly due to lack of oxygen, become injured through contact with the stream bed, or simply be unable to enter the culvert at all (Hotchkiss & Frei 2007). Ideally, water depth within culverts should be maintained at levels similar to natural waterway depth, but minimum depths may also be set with consideration of expected fish migration characteristics (such as fish size, number of fish migrating) relative to flow conditions.

It is reported that in some circumstances, efforts to limit water velocity by installing wide culvert designs (in particular multi-cell box culvert installations) can lead to the creation of shallow water depths through the culvert barrels which in turn hinders successful fish passage (phone conversation with Dr J. Watson, Jan 2020). Recent research has shown that passage success reduces with reducing water depth for larger fish, (phone conversation with Dr J. Watson, Jan 2020). This indicates that designing culverts which will contain shallow water depths during times when larger bodied fish are attempting passage may result in the creation of an unintended barrier. This would be especially detrimental to adult fish migrating upstream to spawn, as this is a temporally critical life history stage for these species (Kapitzke 2010b). If possible, the water depth through the culvert barrel should be maintained as close as possible to the natural stream depth for flow conditions under which attempted fish passage would be expected (Franklin et al. 2018).

Water depth is a key consideration for fish passage identified by Franklin et al. (2018), which states that minimum water depths should be defined at the low fish passage design flow (95% Average Exceedance Probability (AEP) in NZ) (discussed further in Section 2.6). The minimum allowable water depth will vary depending on the fish that will be attempting passage at any given time, and in all cases the depth provided should be sufficient to fully submerge the largest fish that will be attempting passage at any one time (Franklin et al. 2018).

The Victorian guidelines recommend that a minimum depth of 0.3 m be provided for small and medium fish, and also recommend that culverts maintain natural stream depth (O'Connor, Stuart, & Campbell-Beschorner 2017). A minimum water depth of 0.2 – 0.5 m for wet cells is recommended by Fairfull & Witheridge (2003) for NSW fish passage. The Queensland SDAP code does not specify an acceptable water depth, instead broadly stating that hydraulic conditions (depth, velocities and turbulence) must allow for passage of all fish attempting to move through the structure (Queensland Department of Infrastructure, Local Government and Planning 2017). TMR reports that a general rule of thumb for minimum water depth in Queensland is 100 mm (0.1 m).

Minimum water depths for successful fish passage are also considered by design guidelines specified in various US states as shown in Table 2.7. Some states provide generalised criteria based on fish size, while other states specify minimum depths for specific key fish species. The minimum water depth is set with consideration of the lowest flow conditions during which fish will be migrating, and the size of the fish that will be migrating during this low flow condition (Hotchkiss & Frei 2007).

Table 2.7: Fish passage depth requirements for culvert design in several US states

State	Criteria
Maine	1.5 times fish thickness
Alaska	2.5 times caudal fin height
Washington	0.24 m (0.8 ft) adult trout, 0.30 m (1.0 ft) adult salmon and steelhead
California	0.15 m (0.5 ft) juvenile salmonids, 0.20 m (0.67 ft) adult non-anadromous salmonids, 0.30 m (1.0 ft) adult anadromous salmonids

State	Criteria
Oregon	0.30 m (1 ft) adult steelhead and Chinook salmon, 0.25 m (10 in) other salmon, sea run cutthroat trout and trout over 0.51 m (20 in) in length 0.20 m (8 in) for trout under 0.51 m (20 in), Kokanee and migrating juvenile salmon and steelhead

Source: Hotchkiss & Frei (2007).

2.4.4 LIGHT CONTRASTS

Field observations and targeted research conducted overseas and in Australia has found that certain species of fish are sensitive to sudden changes in light intensity, such as those that may be produced by a typical culvert, or certain fishway designs (Vowles et al. 2014). To date, targeted research which investigates the light sensitivity of Australian fish species in regard to fish passage is limited. Mallen-Cooper (1999b) investigated the effect of an artificially darkened tunnel on fish passage at the Torrumbarry fishway in the Murray-Darling Basin. They found that movement of golden perch was largely unaffected by the tunnel, passage of silver perch was reduced by ~13%, and passage of bony herring was completely stopped. This corresponds with observed diel (over 24-hr period) movement behaviours for the investigated species, including movement during all times of the day and night by golden perch, small numbers of movements by silver perch during dawn and dusk, and exclusive daytime movement by bony herring.

Recent research conducted by Keep et al. (2020) has sought to investigate the behavioural responses of four Australian fish species to varying light conditions within an experimental flume apparatus which was covered with black plastic to eliminate ambient light. Three of the species were diurnal (active primarily during the day), and the remaining species (Australian Bass) was crepuscular (active during twilight conditions) but known to be active at other times during the day and night. Half of the experimental flume was illuminated by artificial LED lighting (~2500 lux), while the other half was left darkened.

It was found that two of the diurnal species tested (Fly-specked Hardyhead and Australian Smelt) showed strong avoidance of the darkened areas within the experimental flume. This corresponds to the behaviour of the Australian Smelt observed by Jones et al. (2017), which were observed in significantly lower numbers as light intensity was reduced in an experimental fishway on the Murray River. The thresholds for the hardyhead and smelt to begin entering the darkened area of the flume varied between species, with less than 50% of hardyhead individuals entering for light intensities less than 200 lux, and 75% of smelt entering at a light intensity of 25 lux.

Light intensity during daylight hours within a number of Queensland box culverts ranging from 3–8 m in length was measured by Keep et al. (2020). It was found that light levels in the middle of the tested culverts were ~3 lux regardless of the culvert length. Light intensities at the entrances and exits of the culverts tested ranged from 5–120 lux. If fish in the field were expected to behave identically to those tested in the laboratory, the culverts tested would be barriers to passage for the Hardyhead and Smelt species tested by Keep et al. (2020). There are several factors which may override avoidance behaviour by diurnal fishes however, including (Keep et al. 2020):

- the presence of predators and food
- schooling effects
- personality of individual fishes
- rheotactic response to water flowing through a culvert
- biological need to pass barrier and reach spawning grounds.

The first three points detailed above are hard to quantify, and it is unlikely that these factors could be relied upon to facilitate consistent successful passage through darkened culverts. Rheotactic response and biological impulses may however be more dependable factors which allow fish to overcome avoidance behaviour of darkened spaces.

Field data showing evidence of rheotactic response or behaviour due to obligate migration in relation to darkened culverts is sparse, but one example is provided by Amtstaetter et al. (2017) who observed movement behaviour of the diurnally active *Galaxias spp.* (Common Galaxias) to be unaffected by a 70 m darkened culvert along an upstream migration path. Common Galaxias is a catadromous species that migrates to the sea as adults to spawn and migrates upstream as juveniles and adults post-spawning.

Further research focusing on target species could potentially determine whether the aforementioned factors can be relied upon to facilitate fish passage of darkened culverts. If low light levels are thought to be a critical barrier, provision of a light source which emits several hundred lux (either artificial light or natural light through a ceiling grate) is likely to be sufficient to encourage passage by fish which would otherwise avoid a darkened culvert (Keep et al. 2020). Keep et al. (2020) note that the collection of further data on lighting threshold behaviour for a wider range of fish species could better inform fish passage design with regard to lighting requirements.

Phone discussion with T. Marsden in February 2020 indicated that a key consideration for light contrast remediation is the provision of a gentle, or dappled transition between light and darkness. This can potentially be provided by well-placed foliage, but this would need to be closely maintained to ensure that its intended function is achieved and that it does not begin to pose a risk to structure or roadway functionality.

2.4.5 VERTICAL BARRIERS (HEIGHT DIFFERENCES)

Australian fish typically show poor swimming and jumping ability, which makes the height differences which result from excessive head loss associated with perched culverts an often-insurmountable barrier (Gordos et al. 2007; Hyde 2007). A drop of only 15 cm is enough to bar passage to nearly all Australian fish species, which includes the majority of Queensland fish species (Kapitzke 2010b). This is in contrast to the salmonid fish species commonly found overseas in the US and elsewhere which have developed to be innately strong jumpers due to their typical habitats (Hotchkiss & Frei 2007).

Potential options for remediation of vertical barriers include installation of scour protection which prevents scouring around the culvert entrance and exit; installation of a rock ramp fishway which allows fish to ascend a gentle slope; or installation of a tailwater weir (with fishway if required) which maintains a sufficient water level across the culvert entrance and exit during flows where fish passage is required (O'Connor, Stuart, & Campbell-Beschorner 2017).

Often a culvert may present a vertical barrier during times of low flow which is 'drowned out' during higher flows. In this case, the structure may not be a barrier to migrating species which are triggered by higher flows but may prove insurmountable to species which undertake movements during low flow conditions and cannot gain passage against higher flows. Such a structure may also present a barrier to species migrating on higher flows if the hydraulic conditions within the culvert are prohibitive to passage during these flows. With these points in mind, it is desirable to eliminate vertical barriers from all structures where fish passage is required, although careful consideration of the fish species attempting passage, including the flow conditions (whether or not the vertical barrier is drowned out) during which they will be migrating and their swimming abilities, may reduce this requirement.

2.4.6 WATER TEMPERATURE

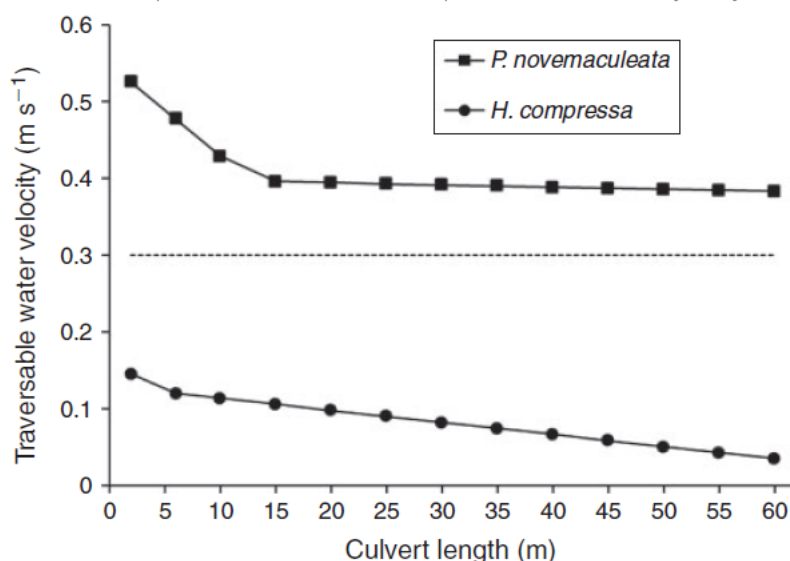
Research has shown that sudden reductions in water temperature can result in reduced fish swimming ability depending on the conditions that the fish is acclimatised to (Rodgers et al. 2014). This means that the velocities produced within a culvert may be passable by fish under certain temperature conditions but may be impassable if there is a reduction in water temperature such as that which may result from the release of environmental flows from a dam. Such an event will lead to increased flows in the waterway, which may be a trigger for migration during which fish passage through culverts and other in-stream structures would be required (Amtstaetter, O'Connor & Pickworth 2015). For waterways where this is likely to occur, reduced fish swimming abilities may need to be factored into fish passage design criteria.

Fish swimming performance in general is highly sensitive to water temperature (Watson et al. 2019) and natural waterways will typically undergo significant seasonal, daily and spatial variation in water temperature which will impact upon fish swimming ability (Caissie 2006). It may be unrealistic to expect culverts to pass fish under all temperature conditions if fish swimming ability is significantly reduced at lower temperatures. Further research could be conducted in this area to determine typical water temperatures within and in the vicinity of culverts at times when fish are attempting passage.

Primary fish migration events for many species occur during times of favourable water temperature, or when water temperatures begin to increase since this is a migratory trigger for many species (Kapitzke 2010b). For example, Duboulay's rainbowfish are generally observed to spawn at water temperatures between 22 and 27 °C (Pusey, Kennard & Arthington 2004). Fish are generally sighted in significantly lower numbers during the cooler months of the year when water temperatures are naturally lower (Telephone conversation with Dr J. Watson, Jan 2020). Rodgers et al. (2014) state however, that significant migration events for *H. compressa* (empire gudgeon) and *P. novemaculeata* (Australian bass) occur between autumn and winter and between late winter and early spring, meaning that swimming ability at 20 °C as shown in Figure 2.20 is likely to be relevant to these species during spawning migrations.

The swimming ability for empire gudgeon determined by Rodgers et al. (2014) is comparatively lower than what was later measured and estimated by Watson et al. (2019), from which it was predicted that empire gudgeon would be capable of traversing an 8 m culvert against a stream velocity of 0.3 m/s. This may be due to differences in test methods, or the characteristics and behaviour of the fish that were tested. The empire gudgeons tested by Watson et al. (2019) were larger than those tested by Rodgers et al. (2014) (mean 5.3 cm vs. mean 4.9 cm), which may have contributed to the increased swimming ability measured by Watson et al. (2019).

Figure 2.20 Predicted culvert traversability for empire gudgeon (*Hypseleotris compressa*) and juvenile Australian bass (*Percales novemaculeata*), at 20 °C and at likely body size during migration



Source: Rodgers et al. (2014).

2.4.7 STREAM GRADIENT

It is generally thought that fish which can be found in streams with steeper gradients will possess stronger swimming ability compared to fish which prefer gently sloping habitats (O'Brien et al. 2016). This was a consideration made for the stream classifications applied in developing the *Queensland waterways for waterway barrier works* spatial data layer which classifies streams according to their fish passage requirements. For the spatial data layer, streams with gradients greater than 6% were considered as not requiring fish passage works for stream crossings.

In most cases, the gradient of the installed culvert should match that of the stream on which it is located. Where the gradient of the culvert is steeper than the stream, higher velocities through the culvert barrel will result, which can lead to scouring and the creation of an excessive velocity fish passage barrier. The majority of fish passage design guides specify that changes to natural stream gradient should be avoided or minimised (Franklin et al. 2018). The US California guidelines state that a bridge should be used for stream gradients above 8%, and that culverts can be placed on a gradient less than that of the stream for active channel design (encouraging accumulation of natural substrate through the culvert), but only for stream gradients up to 3%. Typically, box culverts and concrete pipe culverts are installed on a 0.5–1% maximum gradient so excessive gradient should not be an issue. Stream gradient may be an issue where a corrugated metal pipe is being lined (typically laid at a gradient of 3–5% due to roughness) with a concrete liner pipe that has to be laid at a gradient of 0.5–1%. This can cause problems with alignment of the barrels.

2.5 FISH PASSAGE GUIDELINES REVIEW

Guidelines for fish passage at culverts in NSW, Victoria, South Australia and New Zealand have been reviewed with some comparison made to the current Queensland guidelines. From this review, current fish passage design considerations in each jurisdiction have been identified. No specific guidelines for fish passage provision at large or small in-stream structures could be found for Tasmania, Western Australia or the Northern Territory.

The NSW and Victorian guidelines are generally less rigid compared to the Queensland guidelines as there is more scope to tailor designs based on the specific fish passage requirements of each site. Best practice design guidance/criteria are provided by each guideline, and it may be reasonable to assume that for a culvert design to be approved at least some of these features would need to be adopted.

2.5.1 QUEENSLAND

Fish habitat in Queensland is defined under the *Fisheries Act 1994* and includes land, waterways and plants that support the life cycles of fish. Queensland waterways are classified based on fish passage importance, with a system of four waterway classes (purple, red, amber, and green) for freshwater streams, and a separate classification for tidal waterways (grey) (O'Brien et al. 2016). Works that may disturb or inhibit the free movement of fish within defined waterways are termed 'waterway barrier works' and acceptable performance outcomes for these works are defined by *State code 18: Constructing or raising waterway barrier works in fish habitats*, which is part of a suite of State Development Assessment Provisions (SDAP) (Queensland Department of Infrastructure, Local Government and Planning 2017). The installation of new culverts and the rehabilitation of existing culverts fall under the definition of waterway barrier works and must comply with the performance outcomes outlined by the SDAP code.

To supplement the SDAP code, a set of Accepted Development Requirements (ADR) (Queensland Department of Agriculture and Fisheries 2018) for waterway barrier works have been developed. The ADR outline standardised prescriptive requirements for waterway barrier works on red, amber and green waterways. If these conservative requirements are complied with, the works can be undertaken without a development approval. Works that do not comply with these requirements are termed 'assessable development' and are subject to a development approval process wherein the proposed works are assessed against the benchmarks set by the SDAP code. All works on purple and grey waterways are assessable development and require a development approval.

The SDAP code is outcome-focused, and specifies broad requirements for waterway barriers including that hydraulic conditions within the limits of a structure must allow for passage of all fish at all flows up to drownout of the structure, drops in bed elevation are avoided, waterway bed gradient is maintained at natural levels, roughening is applied to simulate natural bed conditions, and structures are regularly inspected and maintained to prevent blockages. Specific requirements for culverts are comparatively more prescriptive, with a selection of requirements including the need to install culverts which span 100% of natural stream width,

provision of roughening elements on bankside sidewalls and the provision of a contiguous lower velocity zone for at least 100 mm from the wall of the culvert throughout the length of the culvert and wingwalls.

The ADR prescribes an accepted culvert design for red-mapped waterways which includes a requirement for roughening elements to be included along the wall of the culvert barrel, and the wingwalls. If baffles are used as the roughening elements, a design is prescribed. The baffle design consists of full height side angle baffles of a set size placed at a defined interval along the culvert barrel wall and wingwalls. Other requirements include that the width of a culvert array must span 100% of the stream low flow channel, and gradient is limited to natural stream gradient.

In summary, the Queensland fish passage requirements (ADR) provide a prescribed solution and outcome-driven solutions for culvert designs which do not meet these criteria to be assessed under a development approval. For a culvert to be approved under this process, it must be possible to prove that the proposed design will allow for sufficient fish passage as defined by the SDAP code. To achieve this, there must be sufficient understanding of the needs of fish which are attempting passage, which is currently not clear, and generally the prescribed solution is relied upon as a fallback.

2.5.2 NEW SOUTH WALES

Fish passage design for small structures in NSW is controlled by the *Policy and Guidelines for Fish Habitat Conservation and Management* (Fairfull 2013) in the first instance, which references the relevant legislation controlling fish passage development, the *Fisheries Management Act 1994*. Similar to Queensland practice, NSW DPI considers habitat type and waterway class when assessing development proposals which may create a barrier to fish passage (Fairfull 2013). Three habitat types are considered in NSW, along with four waterway classes ranging from high importance marine, estuary and perennial freshwater habitats (Class 1) to unlikely fish habitat consisting of intermittent waterways with little or no defined drainage channel (Class 4) as shown in Table 2.8.

Table 2.8: NSW waterway classification guidelines for fish habitat

Classification	Characteristics of waterway type	Minimum ⁽¹⁾ recommended crossing type
Class 1 Major fish habitat	Major permanently or intermittently flowing waterway (e.g. river or major creek), habitat of a threatened fish species.	Bridge, arch structure or tunnel.
Class 2 Moderate fish habitat	Named permanent or intermittent stream, creek or waterway with clearly defined bed and banks with semi- permanent to permanent waters in pools or in connected wetland areas. Marine or freshwater aquatic vegetation is present. Known fish habitat and/or fish observed inhabiting the area.	Bridge, arch structure, culvert ⁽²⁾ or ford.
Class 3 Minimal fish habitat	Named or unnamed waterway with intermittent flow and potential refuge, breeding or feeding areas for some aquatic fauna (e.g. fish, yabbies). Semi- permanent pools form within the waterway or adjacent wetlands after a rain event. Otherwise, any minor waterway that interconnects with wetlands or recognised aquatic habitats.	Culvert ⁽³⁾ or ford.
Class 4 Unlikely fish habitat	Named or unnamed waterway with intermittent flow following rain events only, little or no defined drainage channel, little or no flow or free standing water or pools after rain events (e.g. dry gullies or shallow floodplain depressions with no permanent aquatic flora present).	Culvert ⁽⁴⁾ , causeway or ford.

1. In all cases, bridges are preferred to arch structures, culverts, fords and causeways (in that order).
2. High priority given to the 'High Flow Design' procedures presented for the design of these culverts – refer to Design Considerations section of this document, or engineering guidelines (Witheridge 2002).
3. Minimum culvert design using the 'Low Flow Design' procedures; however, 'High Flow Design' and 'Medium Flow Design' should be given priority where affordable (refer to Witheridge (2002)).
4. Fish friendly waterway crossing designs possibly unwarranted. Fish passage requirements should be confirmed with the local fisheries department/authority.

Source: Fairfull and Witheridge (2003).

Waterway classification is based on the following indicators:

- hydraulic geometry (stream shape and size)
- frequency of stream flows (perennial, intermittent or ephemeral)
- presence of aquatic habitat units (pools, riffles, vegetation, snags)
- presence of threatened or protected fish species and other native fish
- connection to adjacent habitats (e.g. floodplain wetlands).

The NSW Guidelines state that the paper, *Why do Fish Need to Cross the Road? Fish Passage Requirements for Waterway Crossings* (Fairfull & Witheridge 2003) must be followed by anyone intending to design and construct a waterway crossing in NSW. The NSW Requirements refer to three culvert design (high flow, medium flow and low flow) methods as follows:

- Effective flow area under the waterway crossing should be at least equal to the natural or existing flow area of the channel below the deck/crest level of the crossing ('High Flow Design').
- Culvert designed such that the effective flow area is at least equal to the natural or existing channel flow area below the roof of the culvert ('Medium Flow Design'). A Medium Flow Design also requires the depth of the deck slab to be minimised.
- At a minimum, the culvert should be designed to maximise the geometric similarities of the natural channel profile from the bed of the culvert up to a flow depth of 0.5 m ('Low Flow Design').

2.5.3 VICTORIA

Fish passage in Victoria is legislated by the *Fisheries Act 1995* and other waterway legislation including the *Water Act 1989*, *Fisheries Act 1995*, *Flora and Fauna Guarantee Act 1988* and *Conservation, Forests and Lands Act 1987*. Guidelines for fish passage at small structures (O'Connor, Stuart, & Campbell-Beschorner 2017) were developed as an action of the Victorian Waterway Management Strategy (Victorian Department of Environment and Primary Industries 2013). The objectives of the guidelines were to outline:

- categories of small barrier types and their adverse impacts
- the design process for remediation at small structures
- remediation options.

The guidelines cover remediation options for existing culverts as well as other potential barriers including causeways, fords and weirs. The guidelines provide a set of generic design features (criteria) which can be applied when designing a new culvert, and it could be loosely assumed that new culverts that utilise these features are most likely to be approved for construction. The following key elements are identified for design of effective fish passage remediation options for small structures, including culverts:

- stakeholder engagement
- intervention and fish passage objectives, for example:
 - pass all fish species present downstream of the structure
 - pass fish of size range 40–700 mm
 - provide passage for fish for the full range of the headwater and tailwater levels and stream discharge within which they migrate
 - provide fish passage in both upstream and downstream directions
- budget considerations
- site characteristics
- local fish community.

The Victorian guidelines state that defining realistic and contemporary objectives for fish passage is a key part of the design process for remediation of fish passage at small structures (O'Connor, Stuart, & Campbell-Beschoner 2017). The guidelines note that poorly documented or thought out objectives may lead to less than optimal functionality. Ecological objectives are key to setting performance criteria for a fish passage remediation project, and it is noted that a conceptual model of fish movement in relation to stream flow can be useful to summarise biological data.

The guidelines state that the two generic variables that most influence the design and cost of fishways and other fish passage remediations are:

- the target range of flows over which the fish passage facility will be required to operate
- the makeup of the local fish community.

A key difference between Victorian and QLD/NSW fish passage policy is that there does not appear to be a system of waterway habitat classification in place for Victoria. This means that there is no prescription of certain solutions for certain habitat types, and that each fish passage project needs to be assessed on a case-by-case basis. Fish passage objectives need to be determined for each project, and an appropriate solution that will meet these objectives selected. This solution may be selected from those provided in the guidelines, but it does not seem that possible solutions are strictly limited to those provided.

Some discussion on the setting of biological and hydraulic performance standards for fishways is provided in the Victorian *Performance, operation and maintenance guidelines for fishways and fish passage works* (O'Connor, Mallen-Cooper & Stuart 2015). These were not developed primarily for culvert fish passage, but the methods involved in setting performance standards may be able to be adapted. Performance standards are defined as:

1. **Biological Performance Standards.** This is the actual measure of fishway function, and may include the movement of a particular species and size class of fish through the fishway, or changes to the upstream fish community (e.g. the fishway is required to pass Australian Grayling with > 40 mm fork length).
2. **Physical and Hydraulic Performance Standards.** These include specific measures of depth, velocity, turbulence, etc. designed to pass a particular species and size class of fish (e.g. the fishway should have minimum cell dimensions of 2 x 3 m to minimise turbulence levels, and maximum velocities of < 1 m/s to pass juvenile Australian Grayling).

The guidelines state that the hydraulic standards for passage within fishways are specific to biogeographic regions and the species/sizes of fish present, and performance criteria are provided which are identified as being currently used in eastern Australia (criteria provided for reference in Appendix C). These criteria include minimum fishway water depths, maximum water velocities, and maximum turbulence calculated from head loss and pool volume. Differing criteria are specified for small, medium, and large-bodied fishes, and the size range of fishes which fall into each of these categories varies depending on the fishway design and the specific type of criteria. The criteria specified by the guidelines are not necessarily limiting, but alternative criteria would need to be justified by knowledge of the biological and ecological needs and capabilities of the fish attempting migration. These are not particularly well-defined for most fish species, so it is likely that the default criteria are relied on in most situations.

Some discussion is provided around proportional passage of certain fish life cycle stages (i.e. what percentage of fish attempting passage should be successful) and the setting of acceptable delays to passage at certain life cycle stages based on water flow magnitude. It is noted that the proportional passage of fishes should be as close to 100% as possible, but realistically it will be less and will be defined by the ecological objectives (O'Connor, Mallen-Cooper & Stuart 2015). A 95% passage success target for each migratory life stage of each species is suggested as a generic guideline, and the setting of an appropriate set of objectives for proportional passage is discussed in Box 2 (Figure 2.21). The discussion presented in this figure highlights the fact that passage success lower than the generic guideline can be acceptable if the ecological requirements of a target species are well understood.

It is stated there are three major impacts that delay to migration may result in: reduced or failed spawning, increased predation and increased legal and illegal fishing (where applicable). The setting of an appropriate migration delay relies on a good understanding of migration ecology for target species and the criticality of each migration movement. For example, juvenile catadromous fish which are attempting upstream migration away from the estuary should not be delayed for any more than two tidal cycles due to risk of predation, but Golden Perch undertaking spawning migration may be delayed for less than two days.

Figure 2.21 Setting of proportional passage objectives

Box 2. Proportional passage of a life stage

A proportion of the population needs to pass the barrier in order to maintain sustainable populations. Using the proportional passage of a life stage of a species has more sensitivity than using all life stages of a species in one group, because the ecological priorities of adult and juvenile fish can be different, and large numbers of one life stage (juveniles are usually more numerous) can numerically dominate the data. For example, to maintain sustainable populations of Australian Grayling, it may be necessary to pass 95% of adults returning upstream following their downstream spawning migration, whereas the more abundant juveniles moving into freshwater habitats may only require the passage of 90% of fish to achieve this. Proportional passage as a standard can vary, depending on conservation status, distribution and ecological objectives for the target species. For example, a species that has a dispersal migration each summer and is abundant upstream and downstream would have a lower standard of passage than a threatened species with a small population undergoing a spawning migration. Typically, measuring proportional passage success is performed by comparing species composition, abundance and size range at exits and entrances. Determining the proportion of fish that are required to pass to maintain a sustainable population is more difficult to ascertain and will depend on the ecology of the species (e.g. number of eggs in a fecund female or number of dispersing juveniles), the ecology of the migration (e.g. adult spawning or juvenile dispersal migration) and the status of the species (e.g. common or threatened). Significantly, establishing migration patterns identifies the proportional passage of a life stage (e.g. passage of 90% of juvenile Golden Perch) required to achieve the ecological objective.

Source: O'Connor, Mallen-Cooper and Stuart (2015).

2.5.4 SOUTH AUSTRALIA

The South Australian guidelines for fish passage at small structures are provided by a relatively brief appendix to the Government of South Australia Protecting Waterways Manual. This provides limited guidance which has primarily been sourced from other Australian guidelines, with reference made to Fairfull and Witheridge (2003), Kapitzke (2010c) and the Queensland guideline FHG 001 (Cotterell 1998) which is currently under review. Design principles identified by the SA guidelines include:

- design of culverts for three differing flow capacities:
 - fish passage during low flows
 - fish passage during high flows
 - flood event capacity
- invert levels designed to reflect natural level of stream bed
- provision of resting areas if fish must negotiate drop or apron
- use of bottomless culverts/pipes or setting of the culvert base into the stream bed
- placement of natural sediment from the site along the bottom of the culvert
- roughening of culvert base during concrete pouring to create small depressions which trap sediments

- where dark conditions within a culvert may inhibit fish passage, consideration should be given to minimising structure width or incorporating a grate/skylight in the top of the culvert.

2.5.5 NEW ZEALAND

The NZ *Fish Passage Guidelines for structures up to 4 metres* provides separate design guidance for the design of new structures and the design of remediation options for existing structures (Franklin et al. 2018). For new structures, either stream simulation design or hydraulic design is accepted as a design method. A variety of remediation options for existing structures are also presented and discussed including various types of baffles, mussel spat ropes, as well as ramps used to overcome head loss scenarios.

Stream simulation design has been discussed previously in a subsection of Section 2.4.1. It involves the design of a wide single-barrel culvert at natural stream gradient which encompasses the bankfull width of the stream. This allows natural substrate to accumulate through the culvert barrel, and ideally produces conditions nearly identical to those found in the adjoining stream, which should not create a barrier to fish passage.

Hydraulic design in the context of the *Fish Passage Guidelines* refers to the design of culverts to produce certain hydraulic conditions which will meet biological fish passage needs while providing appropriate hydraulic conveyance capacity. Hydraulic performance standards for the structure may be defined according to either the hydraulic conditions in the adjoining stream (i.e. water velocities, depths across a cross-section) or swimming capabilities and behaviour of target organisms. In either case, appropriate velocities and water depths through the culvert barrel are determined for a range of stream flows during which fish are expected to be attempting passage.

A set of minimum standards for culverts designed using hydraulic design are provided. A selection of these standards includes:

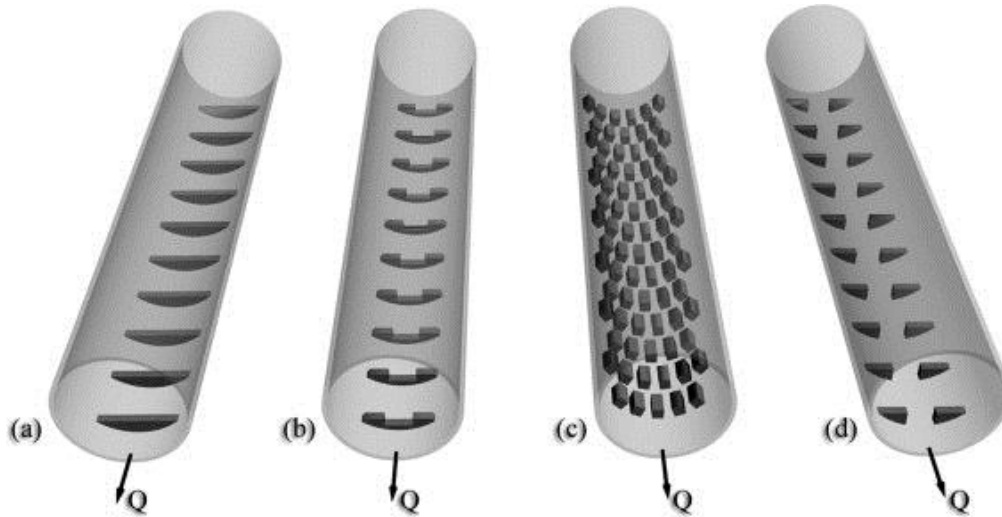
- a requirement to define high and low fish passage design flows (discussed in Section 2.6)
- minimum culvert span based on stream bankfull width
- embedment of 25–50% of the culvert height or use of open-bottomed culverts
- mean cross-sectional velocity in the culvert over the fish passage design flow range is equal or less to the greater of:
 - mean cross-sectional water velocity in adjacent stream reaches, or
 - the maximum allowable water velocity calculated from fish swimming speeds of agreed target fish species and/or life stages.

Data on fish swimming speeds for NZ species is very limited, and only one species (inanga, known as common galaxias in Australia and typically found in the southern states) has been comprehensively studied with regard to the relationship between swimming ability and fatigue. This is a small-bodied and relatively weak-swimming species which has been considered to be representative of small-bodied and juvenile fish in New Zealand.

For the remediation of existing structures, the NZ *Fish Passage Guidelines* discusses various ramp, baffle and mussel spat rope solutions. Rock ramps and other more novel solutions such as moulded plastic ramps have been used to overcome perched culvert barriers in NZ, but not all of these solutions may be appropriate for Queensland fish species as NZ species typically have some climbing ability unlike Australian species. Baffles are primarily recommended for use in the rehabilitation of existing culverts, and the guidelines state that baffle installation should be a last resort for new structures.

Spoiler baffles (Figure 2.23) are currently recommended for use in culverts, and the *Fish Passage Guidelines* provide a synthesis of CFD modelling results and field trial findings for this baffle type. Weir baffles are also discussed, but these are not recommended due to research showing fish getting stuck between baffles (Feurich, Boubée & Olsen 2012). Four types of baffle systems for pipe culverts are illustrated in Figure 2.22, including (a) weir baffles, (b, d) slotted weir baffles, and (c) spoiler baffles.

Figure 2.22 Baffle systems for pipe culverts



Source: Franklin et al. (2018).

Figure 2.23 Pipe culvert spoiler baffles under low flow conditions



Source: Franklin et al. (2018).

Various monitoring strategies are described along with their benefits and drawbacks, including before-and-after-impact surveys, mark and recapture studies, biotelemetry and other simpler methods including fish counting, video cameras and visual checks. The importance of monitoring fish passage solutions is highlighted in the following situations:

- high value fish communities or ecosystems are present upstream of the structure
- unproven designs are being used
- proven designs are being used in novel situations

- retrofit solutions form only one component of an instream structure
- multiple structures exist within a waterway causing cumulative effects
- selective barriers are being used to manage the movement of undesirable species.

The definition of passage success is discussed, and it is noted that the performance of any fish passage structure will vary depending on the type of structure and the target species along with specific site conditions. Proportional passage success is by default required to be 100% for culverts and fords in accordance with New Zealand *Freshwater Fisheries Regulations 1983* which state that:

No person shall construct any culvert or ford in any natural river, stream, or water in such a way that the passage of fish would be impeded, without the written approval of the Director-General incorporating such conditions as the Director-General thinks appropriate.

This stipulation is similar to what is specified by the Queensland SDAP codes, and effectively requires the applicant to produce sufficient evidence to demonstrate that any departure from 100% passage success (i.e. unimpeded fish passage) is supported by proof that the fish population will not be adversely impacted. The NZ Guidelines recommend that fish passage performance standards including acceptable proportional passage success and passage delay are developed on the basis of well-defined ecological objectives which have been developed with consideration of target fish species for a site.

The NZ Guidelines reference the Victorian *Performance, Operation and Maintenance Guidelines for Fishways and Fish Passage Works* (O'Connor, Mallen-Cooper & Stuart 2015) when discussing ecological objectives and biological/hydraulic performance standards (refer to Section 2.5.3), and although a species specific example is provided, there does not appear to be any general rule of thumb for passage success other than the legislative target of 100%. The importance of considering passage success in a catchment context is highlighted, where multiple culverts or other partial barriers may have a cumulative effect on the reduction of fish present upstream, but a rule of thumb is not provided for these scenarios as the appropriate approach is likely to be site-specific.

Knowledge gaps and research needs are also highlighted. One key knowledge gap identified is a lack of information on fish swimming ability and migratory behaviour in New Zealand. While New Zealand fish species are mostly different to those found in Australia (with a few exceptions found in southern Australia), there are similar issues relating to the fact that most species are non-salmonid and are therefore weaker swimmers and jumpers than those salmonid species commonly found in the northern hemisphere where the bulk of historic fish passage research has taken place.

Another key question highlighted is related to the ecological consequences of restricted and/or delayed fish passage. The impacts on upstream fish populations of partial barriers (i.e. those which will pass some proportion of the fish population) and the proportion of fish passage required to maintain ecosystem health are not well understood. The impacts of structures which delay fish passage for a certain period (i.e. act as a barrier under certain flow conditions) are also not particularly well understood, with key questions relating to the impact on fish fitness and spawning viability.

There has also been a lack of biological testing undertaken for fish passage solutions in NZ, with limited post-implementation monitoring taking place. This has also been an issue in Australia, and the knowledge gaps identified for NZ fish passage are very similar to those that exist for Queensland and Australian practice.

2.5.6 UNITED STATES

Hotchkiss & Frei (2007) presents a synthesis of methods for the design of roadway-stream crossings for fish passage with a focus on practice undertaken in the United States. These methods are grouped into four categories as follows (summarised in Table 2.9):

- 'no impedance' techniques which span the entire stream channel and floodplain

- geomorphic simulation techniques which create fish passage by matching natural channel conditions within the culvert crossing. This creates wide culverts which exceed channel bed width, typically in the form of large arch culverts.
- hydraulic simulation techniques, which attempt to closely resemble hydraulic diversity found in the natural channels through the use of natural and oversized substrate along the culvert bed. This will create smaller spanning structures compared to geomorphic simulation, although culvert spans will typically have spans close to bankfull width in order to prevent excessive relative velocities within the culvert barrel.
- hydraulic design techniques, which may utilise roughness elements such as baffles and weirs in order to generate targeted hydraulic conditions for flows where fish are attempting passage. These are commonly used for the rehabilitation of existing culverts for fish passage.

While the fish and other aquatic species which reside in US streams are generally quite different to Australian fauna, many of the design methods applied can be adapted for Australian conditions. Design methods such as geomorphic and hydraulic simulation which aim to reproduce natural stream conditions are universally applicable, as the method adopted is by design adapted in order to reproduce the conditions of the target stream each time it is applied.

For wider streams, the use of geomorphic or hydraulic simulation somewhat precludes the use of box culverts, as there are limits on the span of a single precast cell, and the use of multiple cells may result in elevated velocities within each cell relative to the stream channel velocity.

Table 2.9: Summary of fish passage design methods used in the USA

Category	Description	Relative width	Characteristics		
			Biological	Geomorphic	Hydraulic
NA	No impedance	≥ 100 -yr floodplain	Pass all fish and aquatic organisms	Unchanged	Q_{100} unconstricted
1	Geomorphic simulation	$\geq$ bankfull	Pass all fish and aquatic organisms	Natural substrate; mobile bed; stability of substrate usually not checked	Unaltered for Q slightly above bankfull; Check Q_{100}
2	Hydraulic simulation	$\leq$ bankfull	Reported to pass all fish and aquatic organisms	Oversized substrate; stationary bed; stability of bed usually checked	Similar for Q slightly less than bankfull; Check Q_{100}
3	Hydraulic design	Variable; usually $<$ bankfull	Pass target species at target life stage	Artificial channel	Must meet target species and life stage requirements; Check for Q_{100}

Note: Q_{100} = 100-year ARI flood.

Source: Hotchkiss & Frei (2007).

Hansen et al. (2011) details findings from a performance review of culverts designed using best practice fish passage design techniques in the US state of Minnesota. They identified that culvert width must be similar to bankfull channel width for sediment to accumulate in the culvert barrel, since the sediment deposition process is disrupted if higher velocities exist within the culvert barrel relative to the stream channel. They also identified head cuts as an issue that may occur when a culvert is recessed or embedded below the natural surface of a stream. Scour protection on the inlet side of culverts may be installed to protect against the propagation of upstream head cuts.

2.5.7 DESIGN CRITERIA PROPOSED BY KAPITZKE

A suite of fish passage guidelines for small structures was developed by Ross Kapitzke for the former Queensland Department of Main Roads and published in February 2009, with the most recent version published in April 2010. These guidelines consist of eight parts designated A to I, including an introduction (part A), which cover topics including

- fish migration and movement behaviour
- fish migration barriers and options for remediation at road crossings
- fish passage design at the road corridor scale
- fish passage design at the site scale
- baffle fishway designs for pipe and box culverts
- rock ramp fishway design
- design drawings for fishway projects completed in the Tully-Murray and University Creek (Townsville) catchments.

As part of their suite of fish passage guidelines, Kapitzke (2010b) proposed a set of design criteria for the provision of fish passage for culverts in Queensland. They note that a diverse range of fish species corresponding to various sizes, maturities and swimming abilities may attempt to pass a road culvert in order to undertake key migratory phases of their life cycle, or facultative movements which otherwise support fish life cycles. Key factors include:

- consideration of characteristics of fish that will be attempting migration
 - critical and burst swim speeds
 - swim behaviours such as station holding
 - migratory behaviours
 - other relevant information
- the determination of a design flow range

Three bands of flow condition based on water depth were proposed by Kapitzke (2010d) for fish passage design. It was proposed that fish passage would not be mandatory for the high flow condition, and that three levels of fish passage effectiveness be considered as outlined in Table 2.10.

Table 2.10: Fish passage effectiveness levels and design criteria for provision of fish passage at waterway structures

Fish passage effectiveness	Fish passage provisions for design flow conditions – upstream migration		
	Low flow (flow up to approx. 0.5 m deep)	Medium flow (from approx. 0.5 m to approx 1.5 m deep)	High flow (flow in excess of approx. 1.5 m deep)
Level 1 – conservative	All native fish species, life stages and maturity	All but outlier ⁽¹⁾ native fish species (e.g. poor swimmers)	Not mandatory for any native fish species
Level 2 – intermediate	All native fish species, life stages and maturity	Not mandatory for any native fish species	Not mandatory for any native fish species
Level 3 – restrictive	All but outlier ⁽¹⁾ native fish species (e.g. poor swimmers)	Not mandatory for any native fish species	Not mandatory for any native fish species

1. *Restricted fish community may be identified on the basis of fish species diversity (e.g. icon species, weak swimming species), or on fish life stage and maturity (adult spawning/juvenile dispersal/adult dispersal/facultative movement for adults and juveniles).*

Source: Kapitzke (2010d).

Kapitzke (2010c) advises that fish passage design must be undertaken holistically for the complete structure site. In addition to the culvert barrel, this includes the culvert inlet and outlet, and the upstream and

downstream portions of the channel in the vicinity of the culvert. A generic set of criteria for achieving effective fish passage and hydraulic design as proposed by Kapitzke (2010c) include:

- provide suitable hydraulic conditions (e.g. velocity, shelter, turbulence) in the downstream channel, at the structure outlet, and on the downstream apron to overcome adverse conditions (e.g. high velocities, shallow flow depth, lack of shelter, excess turbulence, water surface drop) and to allow fish to pass upstream during low/medium flows
- provide suitable hydraulic conditions (e.g. velocity, shelter, turbulence) within the culvert barrel and at the structure inlet to overcome adverse conditions (e.g. high velocities, lack of shelter, excess turbulence) and to allow fish to pass upstream during low/medium flows
- provide flow continuity through all fishway zones and a continuous fish pathway and attraction flow to allow fish to readily locate the downstream entrance to the fish passage facilities through the structure and to move upstream through the fishway in response to flow
- provide suitable shelter conditions at the structure inlet and in the upstream channel to allow fish that have passed through the downstream fishway sections to exit the structure and move freely away into the stream during low/medium flows
- minimise obstruction to flow through the culvert barrels in order to not adversely affect flooding at the structure
- minimise debris accumulation and sediment deposition within the culvert barrels and provide for ready cleaning and maintenance of the waterway structure
- maintain integrity of the waterway structure and provide for transport, drainage and other utility functions at the site.

These design criteria are generalised, and guidance provided relating to what constitutes 'suitable' hydraulic conditions is somewhat vague. Discussion around acceptable velocity conditions in the guidelines has been generally developed based on the author's experiences with fish passage works in the Tully-Murray catchment. For example, it is stated that for an average culvert velocity of 0.5 m/s, resting areas for fish are required to support passage (Kapitzke 2010d).

Kapitzke (2010a) notes that the guidelines compile the findings to date of the James Cook University culvert fishway R&D program, in addition to information from existing literature and concepts developed by the author, but there were still many knowledge gaps and areas where further investigation and development was required. These knowledge gaps related to a range of factors including field and laboratory modelling of various fishway configurations, hydraulic modelling, and design flows and swim speeds for Queensland fish species. Some of these are beginning to be addressed, most prominently through work completed by TMR and by UQ. No further updates to the Kapitzke guidelines have been observed since release, and the current status of JCU fish passage research is unclear.

The Kapitzke guidelines were developed based on research and past projects completed in the Ross River and Tully-Murray catchments which are located in Northern Queensland. This means that the fish and river conditions encountered were typical of these regions and may not be directly representative of other regions of Queensland, particularly west of the Great Dividing Range.

2.5.8 GUIDELINES PROPOSED BY CHANSON AND LENG (2019)

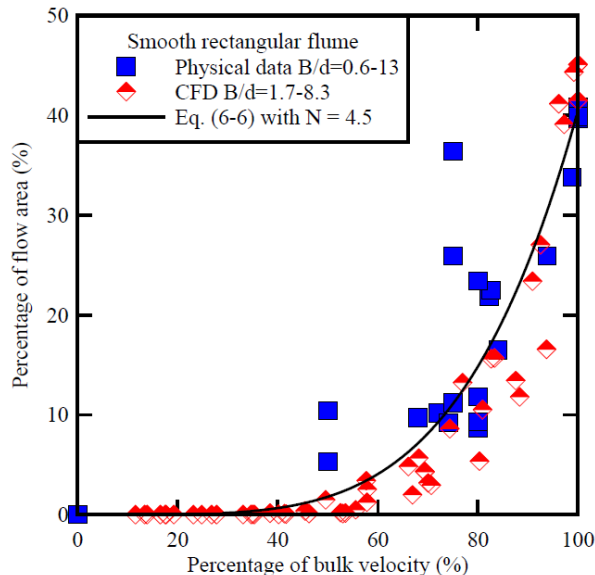
The guidelines proposed by this document are focused on the design of fish-friendly multi-cell box culvert installations, without the need for additional fish passage accessories such as baffles. The approach taken by the guidelines is based on three concepts (Chanson & Leng 2019):

1. Culvert design is optimised for fish passage at low to medium discharges.
2. RVZs are provided along the wetted perimeter in the culvert barrel and quantified in terms of a fraction of the wetted flow area where the local longitudinal velocity is less than a characteristic fish speed linked to swimming performances of targeted fish species.
 - a. The width and depth of the RVZ must encompass the size of the target fish species.

3. The culvert barrel is smooth, without any other form of boundary treatment and appurtenance.

Figure 2.24 illustrates the relationship between percentage of flow area and percentage of bulk velocity for a smooth rectangular flume. This data was obtained for discharges ranging up to 0.3 m³/s per barrel cell and internal barrel widths ranging from 0.1 m to 2.4 m. The figure shows that the target RVZ proportion of 15% of the flow area will experience a velocity roughly 80% of the bulk velocity. This means that to achieve an RVZ velocity of 0.3 m/s, the bulk velocity could be no higher than 0.375 m/s, which may be unrealistic.

Figure 2.24 Relationship between flow area and bulk velocity



Source: Chanson and Leng (2019).

The guidelines are based on past observation and experimentation which showed that fish preferentially swim within RVZs when attempting upstream culvert passage (Wang & Chanson 2017; Wang et al. 2016). Characteristic fish swimming speeds for use with these guidelines could be adapted from the work of Watson et al. (2019) with additional species tested as required. The guidelines were developed with a focus on small-bodied fish species, but it is stated that the methods could be applied for larger and stronger-swimming species.

Due to the nature of the design methodology, the fish-friendly designs produced using the approach are likely to have a larger number of cells compared to a traditional box culvert design. This will increase construction costs, which could potentially be offset somewhat by increased flood discharge capacity, but this may be limited. The design methodology also assumes that a relatively high tailwater depth is achieved during sub-design flow conditions, which may not be viable in many cases. Considering these points, the use of roughening elements in a culvert installation designed using current practice may be economically desirable in many cases.

2.6 DETERMINATION OF DISCHARGE CONDITIONS FOR FISH PASSAGE

Flow magnitudes for fish passage are generally lower than the design flows which are used to design culverts for trafficability, inundation or erosion protection for the roadway crossing (Kapitzke 2010b; O'Connor, Stuart, & Campbell-Beschorner 2017). Certain species of fish are known to migrate in response to flood events however, and in some cases fish passage may need to be provided for certain flood discharges.

The NZ fish passage guidelines (Franklin et al. 2018) indicate that fish passage hydraulic design needs to occur for a certain target range of flows during which fish can be expected to attempt passage. Flows which exceed the maximum fish passage flow are treated as requiring design for hydraulic capacity only, and it is

assumed that fish passage does not need to be catered for during such flow events. Franklin et al. (2018) defines fish passage design flows as follows:

1. Low fish passage design flow (Q_L): $Q_L \leq 95\%$ exceedance flow. Lower limit of fish passage responsibility.
2. High fish passage design flow (Q_H): $Q_H \geq 20\%$ exceedance flow. Upper limit of fish passage responsibility.
3. Design peak flood flow (Q_P): estimation of the highest flow that a culvert should be designed to pass without causing a significant increase in upstream flooding. Fish passage is not expected to be catered for at this flow magnitude.

These are specified as a rule of thumb and have been developed based on NZ conditions. It is possible that Queensland conditions, or conditions within certain regions may necessitate varying limits on fish passage design flow magnitude. The design flow interval may also vary depending on the culvert type and design (i.e. pipe, box, arch). The important point is that fish passage solutions are generally not expected to operate over the full range of flows that a culvert would be expected to experience, and it is important to define operational flows in relation to the expected timing of migratory events and the flows under which they are expected to occur.

The use of high and low fish passage design flows is also common practice in the US, although some states also specify an acceptable delay to migration (Caltrans 2014). Hotchkiss & Frei (2007) notes that the high fish passage design velocity should capture the upper bound for which it is believed that fish are moving in the stream. Caltrans (2014) states that the flow conditions associated with the catchment upstream of the target culvert should be considered when determining high and low fish passage design flows. A range of high fish passage flow guidelines for different US states are shown in Table 2.11, for informative purposes. It is recognised that these guidelines have been developed based on the fish species and hydraulic conditions prevalent in each US state, and are not likely to be directly applicable to Queensland conditions.

Table 2.11: Various US state and agency guidelines for high fish passage flows

Alaska	Washington	Oregon	NMFS SW Region	California Dept of Fish and Game	NMFS NW Region	Idaho
Q_{2d2} : the discharge 24 hours before the 2-yr flood	10% exceedance flow during migration period – species specific	10% exceedance flow during migration period: species specific. Approximate by $Q_{10\%} = 0.18*(Q_2)+36$ where $Q_2 > 44$ cfs. Where $Q_2 < 44$ cfs, use Q_2 .	For adult salmon and steelhead 1% annual exceedance flow or 50% Q_2 . For juveniles, 10% annual exceedance flow.	Standards vary from 1–10% exceedance flow for various groups of fish.	5% exceedance flow during period of upstream migration	< 2-day delay during period of migration

Notes: Q_2 refers to 2-year ARI event.

Source: Hotchkiss & Frei (2007).

The Victorian *Guidelines for fish passage at small structures* (O'Connor, Stuart, & Campbell-Beschorner 2017) highlight the importance of defining the range of flows over which a fish passage solution will be required to operate. The Victorian *Guidelines for the design, approval and construction of fishways* (O'Connor, Stuart, & Jones 2017) provide further guidance which indicates that determining expected stream discharge magnitude and duration during important migration events for target fish species is key to achieving an effective design.

The Victorian *Performance operation and maintenance guidelines for fishways and fish passage works* provides some guidance examples relating to the setting of ecological objectives for fishway operation, which includes reference to the consideration of acceptable delays to fish migration. The Guidelines note that

acceptable delays will vary depending on the species of fish, and the ecological significance of the migration movement in question.

Currently, the Queensland ADR does not provide any guidance on the range of flows for which a fish passage treatment is intended to facilitate passage by target species. The ADR states that for culverts on high impact (red) waterways, 'roughening elements aim to achieve a contiguous lower velocity zone (no greater than 0.3 m/sec) for at least 100 mm width from the wall through the length of the culvert'. There is no guidance provided regarding the range of discharges that the 0.3 m/s contiguous zone must be achieved for. The physics of water means that it is very complicated or likely impossible in many cases to provide a contiguous low velocity zone for all expected culvert discharges. This means that realistically, fish passage treatments need to be designed to operate for a range of target flows during which fish are likely to be attempting passage.

The approach which has been applied for several recent fish passage projects in Queensland involves the consideration of flow frequency analysis and acceptable delays to fish passage based on duration of high flow conditions (personal communication with T Marsden, Feb 2020). In one case, it was demonstrated that fish passage provisions would not be required for an alternative high flow channel at a site since the channel was only expected to be active for a matter of hours once in a ten-year period.

In cases where culvert drown out occurs quickly and flood flows move over the top of the roadway, it can be argued that fish passage solutions do not need to operate for flood flow discharges, since fish can gain passage over the top of the road surface. Conversely, in situations where high discharges occur for long periods of time without road overtopping (common in western Queensland flood scenarios), the operation of fish passage solutions for high discharges must be considered. Large numbers of small-bodied fish have been observed moving in low-velocity regions along the banks of streams during high discharge conditions in western Queensland, and the DAF-specified baffles have been observed to facilitate fish passage through box culverts in these areas, although passage outcomes have not been formerly quantified (personal communication with T Marsden, Feb 2020).

TMR has recently undertaken flow frequency analysis of representative catchments which may be used to facilitate a flow duration/time delay-based approach to assessing fish passage requirements. An approach to design which explicitly considers flow duration is not currently recommended by any guidelines specifically intended for small structure fish passage in Australia or NZ, but the Victorian guidelines for fishway design specify that flow duration curves and flow frequency analysis may be used to predict the range of flows over which a fishway will be expected to operate (O'Connor, Stuart & Jones 2017). These guidelines also note that low frequency, high magnitude discharges can be particularly important as these discharges may be linked to life-history traits such as spawning and dispersal.

3 KNOWLEDGE GAPS AND FURTHER WORK

3.1 FISH MIGRATION

The behavioural patterns of obligate migrators which undertake defined migrations either as adults pre-spawning and post-spawning or as juveniles post-spawning have been fairly well described by Kapitzke (2010b) for species found in coastal north/central Queensland, although the data is not complete. It is acknowledged that a migratory delay of several hours is likely to be acceptable for these species, although this may vary depending on the hydrology of specific catchments and the biological needs of certain species (phone conversation with T. Marsden, Feb 2020). This suggested acceptable delay does not appear to be backed up by any extensive research outcomes, and future work which focuses on quantifying acceptable delays for target fish species and flow conditions may be beneficial if a situation arises where delay of several hours is considered too short.

Further research on migratory behaviour of obligate migrators may be required if an approach similar to that adopted for fishways in Victoria is pursued which requires fish characteristics to be considered when setting biological objectives for a new fish passage structure or remediation (see Section 2.5.3). Such an approach would require comprehensive determination and synthesis of migratory behaviours including timing and criticality of each event. Understanding of swimming ability for target fish would also be required, and the swimming ability data available for Queensland species is not yet fully comprehensive as discussed in Section 3.2.1.

Less well understood are the behavioural patterns of facultative migrators (including but not limited to potamodromous species in eastern and western systems) which move during low-medium flow conditions for various reasons including predator avoidance and food sourcing. Certain wide culvert designs which are intended to be fish-friendly at high flows may prove to be a barrier under low flow conditions if water depths through the culvert are lower than those in the natural channel. This highlights the importance of considering low flow conditions in fish-friendly culvert design, but further definition of acceptable low flows for design is required. Ideally, the water depth within the limits of a culvert structure should not fall below natural stream depth under any streamflow conditions, but if this is not viable efforts should be made to ensure that passage is not inhibited under low flow conditions.

3.2 FISH BIOLOGY

3.2.1 SWIMMING ABILITY

The swimming ability dataset produced by Watson et al. (2019) was intended to be representative of fish species found throughout NSW. Despite this focus, there is considerable overlap with Queensland fish species, especially those found throughout south-eastern coastal streams and the upper Murray-Darling Basin. The current maximum velocity requirement for culverts of 0.3 m/s was well-supported when considering passage over a distance of 8 m, but there were four species out of the 21 tested for which it was predicted that a velocity of 0.3 m/s would prevent passage. As culvert length increases, less species are able to gain passage against a continuous velocity of 0.3 m/s, and further treatment (such as baffles) is likely to be necessary to facilitate passage by most fish for longer culverts.

If baffled culverts are to be relied on (or any design which requires fish to swim in a burst-and-rest pattern), the sprint swimming ability of fish species will need to be considered if velocities in the culvert exceed the critical swimming speed of the target fishes. Fish may employ any combination of sprint, critical and cruising (resting) swimming behaviours to pass a culvert, which complicates the task of estimating passage success based on quantified swimming abilities and expected hydraulic conditions. A structure which is designed on the basis of fish swimming at their critical speed between periods of rest at cruising speed would be most likely to facilitate passage, as fish could be expected to also swim at sprint speed for some part of their

passage attempt. This may result in overly conservative hydraulic requirements, however, since fish could potentially also swim at sprint speed between periods of rest at cruising speed.

There is scope for further research to be conducted on specific Queensland fish species which were not captured in the initial dataset. If this was to be undertaken, it would be important to recreate the conditions which were applied in the initial study to ensure that the results are directly comparable with those obtained for the species which have already been tested (assuming that the test conditions were appropriate). A list of key Queensland fish species was provided by Tim Marsden (supplied in Appendix A), and some advice has been received on which species are unlikely to have swimming abilities which are able to be predicted based on the outcomes of the previous research. These were identified as archer fish and eels (email conversation with Dr J. Watson, Jan 2020).

Several authors have noted that laboratory swimming tests may provide a conservative estimate of swimming ability, and the swimming ability tests conducted by Watson et al. (2019) and others have not been comprehensively backed up by field data. It is difficult to quantify swimming ability in the field, but there are reportedly plans for a full-scale box culvert setup to be established by UQ which could allow for more easily quantifiable research outcomes (phone conversation with Dr J. Watson, Jan 2020). The ongoing TMR field trial of fish baffle treatments in box culverts may also provide some insight into the capability of fish to pass real culverts operating under a range of hydraulic conditions and fish passage treatments, and this will be reviewed in the next phase of this project.

3.2.2 SWIMMING BEHAVIOURS

There is potential for further research to be undertaken which focuses on the impact upon passage success of rheotactic response and station holding behaviour that allows certain species of fish to grasp the substrate and rest while swimming in certain hydraulic conditions. Gathering data relating to the substrate conditions and water velocities for which station holding contributes to passage success will enhance understanding of the velocity conditions under which certain weaker-swimming fish species can gain passage, particularly gudgeons and galaxiids.

Several weaker-swimming species identified by Watson et al. (2019) (which were predicted to be unlikely to gain passage through a typical 8 m long culvert against a velocity of 0.3 m/s) showed evidence of station holding behaviour, although they were unable to effectively station hold due to the smooth Perspex flume used in testing. It is suggested that similar experiments are undertaken for a range of flow conditions with the previously tested fish species (*H. compressa*, *H. galii*, *M. adspersa*, *P. grandiceps* and *R. bikolanus*) and other key Queensland species as required, applying substrate conditions as follows:

1. range of natural substrates typical of tested species stream habitat i.e. gravel, sand, mud etc.
2. artificial substrate in line with current best practice
3. bare concrete
4. corrugated metal

Any laboratory experiments should be augmented by formalised field observations, preferably in culverts with and without natural substrate including box and pipe culverts.

3.3 CULVERT CONSTRAINTS FOR FISH PASSAGE

It is generally accepted that culverts pose a barrier to successful fish passage, and there have been field observations of large numbers of fish immediately downstream of culverts for fish species including bony bream and various gudgeon species (Pusey, Kennard & Arthington 2004). This implies that culverts are acting as a barrier, although the flow conditions under which these observations were made are unclear. There has been some monitoring of fishways on dams and barrages (Marsden, Berghuis & Stuart 2017), but evidence of substantial culvert monitoring outcomes could not be found in the literature.

Overall, the impacts of culverts on fish populations in Queensland do not appear to have been comprehensively quantified. There also appears to be a lack of information available regarding the impacts

of culverts installed using the current ADR baffles and field monitoring may assist in filling this knowledge gap. This monitoring would need to be targeted to investigate both 'fish-friendly' ADR culverts and non-ADR culverts which are thought to be acting as barriers to fish passage. Monitoring may need to be undertaken over a period of years in order to capture a range of flow conditions and allow for the development and fluctuation of fish populations.

3.3.1 VELOCITY

There has been reasonable coverage of the velocity conditions expected within box culverts, with a volume of work being completed by UQ which has looked at both flume testing with a box culvert model, and computation fluid dynamics modelling. The RVZs expected within box culverts have been well-described, and ongoing field testing in Queensland is expected to reveal further insight into how fish respond to box culvert and various baffle configurations. There has been less coverage of the conditions expected within pipe culverts, and there may be value in the application of similar testing and modelling to that applied to box culverts. Further review of overseas studies may also yield some insights in this area, but this is out of scope of the current project and will be considered in a future project year.

3.3.2 TURBULENCE

The current side angle baffle design prescribed by the DAF self-assessable codes is known to generate turbulent eddies downstream of the baffle face, in the 'resting' area between baffles (Witheridge 2020). These eddies should ideally be positioned away from the face of the baffle in order to provide an effective resting area, since certain fish (particularly small-bodied fish) can become disorientated by excessive turbulence and be 'washed' out from the resting area. The formation of turbulent eddies may not be accurately estimated by CFD modelling since eddies, or vortexes may form due to random triggers (Witheridge 2020). It is recommended that the baffle designs recommended by Witheridge (2020) are tested in a field setting using representative fish species, and that various designs are developed and trialled as per their recommendations. The ongoing TMR field trial of fish baffle treatments in box culverts may also provide some insight into the comparative performance of field baffle designs in creating turbulence and the effect of that turbulence on fish passage.

Turbulence may be beneficial to fish passage if the size of turbulent eddies is well-matched to the size of the fish attempting passage, but since the prediction of turbulence is highly complicated it is unlikely to be viable to rely on this effect for positive passage outcomes. Rather, it is recommended that the size of turbulent eddies is minimised for flows where fish passage is required, and roughening elements such as baffles are designed to position areas of turbulence away from low-velocity fish resting areas.

3.3.3 LIGHT CONTRASTS

Laboratory experiments have indicated that certain diurnal species of fish may be inclined to avoid entering darkened culverts (Section 2.4.4). If this behaviour was replicated in the field, it may have a detrimental impact on passage outcomes. Field observations have however shown diurnal fish moving through darkened culverts while migrating.

Further field research is recommended to determine whether factors such as rheotaxis or migratory urges are able to overcome darkness avoidance in the field. This research should be focused on the fish which showed avoidance behaviour in the experiments by Keep et al. (2020), and specific Queensland species which have shown avoidance behaviour in the field (bony bream, mullet) (Queensland Department of Agriculture, Fisheries and Forestry 2014).

The potential benefits of providing a gradual transition at the entrance of a typical culvert should also be investigated for the species identified. If it was found that darkness avoidance can be reliably overcome in the field by either behavioural factors or the provision of a dappled transition, requirements for artificial or natural light provision through culverts may be lessened. Field trials of artificial lighting within a culvert could be combined with a baffle trial to see if the increasing lumens improves fish passage outcomes.

3.3.4 WATER TEMPERATURE

It is generally thought that fish will attempt migration during periods of increased water temperature favourable to their movement. This may not be the case for all species however as identified by Rodgers et al. (2014), and lower temperatures may significantly reduce the swimming ability of fishes. Further field observation and research on species which are reported to migrate upstream during periods of reduced water temperature may be beneficial to determine whether swimming ability at reduced temperatures should be considered in culvert design. Empire gudgeons may be an initial candidate for further research but a fish biologist should otherwise be consulted to establish which species would fall into the required migratory category.

It is also recommended that an initial assessment is undertaken to determine whether there are significant numbers of culverts located on streams which experience environmental releases from dams. If the environmental releases are key to facilitating fish migrations (i.e. normal streamflow increases due to rainfall which would otherwise trigger migration are limited due to upstream dam treatments), it may be necessary to consider reduction in fish swimming ability due to temperature. This would be best considered on a case-by-case basis considering stream hydrology and the fish species present.

3.4 WHEN IS PASSAGE REQUIRED?

3.4.1 CONSIDERATIONS FOR WATERWAYS

Where there is reason to believe that provision for fish passage either may not be required or should be less stringent compared to what is required for the classification of the waterway, it may be cost effective to perform a fish survey with the aim of determining whether fish are present and the species composition of fish if applicable.

A catchment survey which determines the extent of the catchment associated with a certain waterway and structure location may also be appropriate where it is thought that a waterway may not fall under the fish passage requirements. For intermittent watercourses, any investigations would need to be undertaken during times when the stream is active (potentially at least 1-year ARI, but this may be limited by health and safety requirements) to ensure that maximum fish habitat conditions are observable.

There are concerns that in some scenarios, the Queensland Waterways for Waterway Barrier Works spatial layer is applying fish passage requirements for waterways which are highly modified stormwater drains, and some form of legislative instrument to trigger reassessment may be beneficial in terms of arriving at the best possible fish passage solution for environmental and economic requirements. O'Brien et al. (2016) notes that several alternative waterway determination requests had been made to DAF since the implementation of the spatial data layer, and that alternative determinations would be assessed annually with updates to the data layer made as required. The spatial data layer available on the Queensland Spatial Catalogue website (Queensland Department of Agriculture and Fisheries 2016) has not been updated since July 2016. However, it is understood that at the time of writing DAF were undertaking a review project of the spatial layer.

3.4.2 FLOW EVENT CONSIDERATIONS AT INDIVIDUAL STRUCTURES

There is some variance in the literature regarding the flow conditions under which fish passage should be provided for in design. The NZ guidelines provide a minimum and maximum AEP flow for fish passage design, meaning that fish passage must be provided for all fish attempting passage between a minimum flow (95% AEP) and a maximum flow (20% AEP). The NSW guidelines take a different approach, specifying that for flow depths up to a maximum of 0.5 m, a contiguous velocity of 0.3 m/s should be provided through a smooth-bedded culvert.

The Victorian guidelines discuss the importance of determining the range of flows over which a fish passage solution must operate. Previous Victorian guidelines indicated that fishways should operate during 95% of

the range of expected flow conditions for a site, but this has since been withdrawn as it has been recognised that high flows which are outside the 95% of flows may correspond with key fish migration events. As discussed in Section 2.5.3, the preferred approach for fishway design is to match the range of flows that the fishway needs to operate over to the flows at which fish will be migrating.

The wording of the Queensland SDAP code (Department of Infrastructure, Local Government and Planning 2017) appears to be supportive of such an approach (i.e. '...allow for fish passage of all fish attempting to move through the crossing at all flows up to the drownout of the structure'), meaning that if it could be shown that fish would not likely to be moving under certain flows, it would be reasonable to not produce hydraulic conditions conducive to passage under these conditions.

As an initial step, it is recommended that the results of the flow frequency analysis for representative catchments conducted by TMR are compared to the timing of migrations undertaken by representative Queensland fish species. This would aim to identify the discharge magnitudes at which Queensland species are typically moving upstream. This could then be applied to determine the range of discharges over which culverts need to provide fish passage in representative catchments.

3.5 ACCEPTABLE PASSAGE OUTCOMES

What equates to biologically acceptable passage outcomes where a structure acts as a barrier to some proportion of the migrating fish population is currently unclear. As discussed in Section 2.3.1, the field swimming performance of Queensland fish species has generally not been comprehensively quantified, and there is uncertainty surrounding the potential conservativeness of laboratory swimming performance data, particularly for smaller-bodied fishes. Culverts are widely acknowledged to act as barriers to successful fish passage as discussed in Section 2.4, but there is uncertainty surrounding the point at which a culvert becomes an unacceptable barrier, particularly considering velocity and turbulence conditions. Quantification of field swimming performance for Queensland fish species and monitoring of existing culverts both with and without fish passage remediations installed is required to gain a better understanding of how culverts are impacting on fish passage outcomes.

The Queensland SDAP code specifies that hydraulic conditions should allow for fish passage of all fish attempting passage up to drownout of the structure, which can be interpreted as requiring that 100% passage be achieved (Queensland Department of Infrastructure, Local Government and Planning 2017). This is more stringent than what has been achieved for fish passage remediations which have been considered successful in other states, for example the Cardinia Creek pipe culvert rehabilitation in Victoria which achieved a maximum passage success rate of 59% at a certain discharge (Amtstaetter et al. 2017). Similarly, in NSW the remediation of a pipe culvert resulted in an increase from 20% to 69% passage success (Fairfull & Witheridge 2003). It is unclear whether the passage success rate achieved in these cases was ecologically acceptable, although the remediation is likely to have improved ecological outcomes as a result of passage success increases.

The Victorian fishway guidelines (O'Connor, Mallen-Cooper & Stuart 2015) discuss the setting of performance measures for the proportion of passage success. Data which would support the setting of such performance measures for Queensland species is currently either fragmented or deficient in most cases. Despite this, there may be some generalisations that can be made, such as that for catadromous species identified in Section 2.5.3. The work completed by Kapitzke (2006) for fish species within the Tully-Murray catchment may provide a good starting point as it details migratory behaviours and varying degrees of swimming ability data for Queensland fish species.

It is quite likely that the acceptable passage success rate will vary according to the specific species of fish and life cycle stages which are attempting passage, and it is acknowledged that 100% success is the ideal outcome in most circumstances. This is unlikely to be economically feasible for new culvert structures and may be impossible for structures which require rehabilitation or remediation. In these cases, assessment by a fish biologist could be an option to establish what species are present and what level of passage success will be necessary to maintain a healthy population and habitat. The fish passage design criteria to be

developed in Year 2 of this project will aim to produce as close to 100% passage success as possible for new designs, but it is recommended that a trigger for further assessment of acceptable passage outcomes is included for remediation of existing structures.

3.6 DESIGN APPROACHES TO CULVERT FISH PASSAGE

Review of the literature showed that there are two major culvert fish passage design philosophies which are:

1. stream simulation design; or
2. hydraulic design.

The functional requirements of fish generally do not need to be directly considered for the stream simulation design approach, as it is assumed that by replicating the stream conditions fish will automatically gain passage. For hydraulic design, a range of functional inputs are required. These may be set on a case-by-case basis, or generic inputs may be defined for generalised design criteria.

3.6.1 STREAM SIMULATION DESIGN

Stream simulation design requires a single barrel culvert which spans the bankfull width of the waterway, meaning that large arch or embedded pipe designs are commonly used. This method may be more viable for narrower streams high in catchments, where bankfull width may be accounted for with a conventional box culvert design. For larger waterways, some flood immunity benefits may be realised by installing a wide-spanning culvert. This is unlikely to be possible in western catchments due to vertical alignment constraints.

The key limitation for stream simulation design is culvert sizing. Corrugated steel is not a preferred construction material in most situations due to historical corrosion and integrity concerns. Therefore, in many situations the sizing of the culvert is limited to what is available in reinforced concrete pipes and box culverts. Box culverts are available in up to 4.2 m spans, meaning that pure stream simulation design would be limited to streams with bankfull widths at or below this upper limit on span width.

3.6.2 HYDRAULIC DESIGN

Hydraulic design could potentially be similar to the approach currently taken for fishways in Victoria, where a structure is designed based on a combination of biological and hydraulic performance measures. The hydraulic design methodology relies on design parameters being known. This would effectively require the following functional inputs as a minimum:

- swimming performance data (sprint, critical speed) for either a selection of representative species or all species in the catchment
 - swimming performance data should be captured at life stages where the fish would need to migrate upstream
 - at present this is generally accepted in Queensland as 0.3 m/s. This is supported by literature, although the supporting research has been conducted for a limited range of species and life stages.
- seasonal timing and importance of migration events, including fish population data and migration biomass (numbers of fish migrating)
 - determine how long migration could be delayed for, and what proportion of migrating fish need to succeed to meet ecological objectives
 - currently not documented in the literature therefore this would require site-by-site, project specific research and monitoring
- seasonal flow frequency data for the catchment which can be matched to timing of migration events
 - determine flow magnitudes within the waterway based on either gauge data or catchment modelling

- determine likely flow magnitudes during migration events and associated culvert velocities. This is currently not understood or at least documented, so would need to be investigated on a site-by site, project-specific basis.
- currently the ‘sustainable’ level of fish passage from a legislative and ecological perspective is undocumented. The default is to aim for 100%. Potentially, the NZ and previous Victoria guidance of the 95th percentile of flow could be used as the default pursuant to DAF approval.

This dataset could then be used to determine the range of discharge conditions that a culvert would need to provide passage for, and the hydraulic conditions that would be required within i.e. velocity, turbulence. Necessary hydraulic conditions could be produced through any combination of baffles or other treatments, or in some cases where the structure quickly drowns out at high discharges it may be the case that no treatment is required. In this case other flow conditions under which fish would be likely to be migrating would also need to be examined. This would require modelling in both 2D and 3D in order to identify turbulence. This requires computational fluid dynamics (CFD) which is both costly and takes time.

If the hydraulic design approach, which requires extensive input data, was adopted as an option for fish passage design, it would be important to understand the range of situations for which application of advanced hydraulic design would lead to a better outcome than the application of more generalised design criteria. This might be determined by factors such as the importance of fish habitat at the site, expected discharge conditions, or site restraints which preclude the application of the generalised design criteria.

For example, it might not be advisable to spend sizeable amounts of time and money to define the full site-specific functional requirements for a site consisting of a perched, narrow diameter pipe culvert on a purple or red-classified waterway (high importance fish habitat), since the structure (and any innovative steel culvert rehabilitation methods which reduce waterway area) is unlikely to result in suitable passage outcomes. In a case such as this, replacement with a fish-friendly box culvert designed using generalised criteria could prove to be the most cost-effective and ecologically suitable solution.

Post-construction monitoring would be beneficial for structures designed using either stream simulation or hydraulic design. This would aim to ensure that the ecological objectives of the structure are being met e.g. is the structure passing the required proportion of a certain fish species to support upstream population. This would enable confirmation that the methodology is working as designed and potentially identify generalised design principles and criteria that could then be used to design culverts consistently in future.

Situations where a site-specific hydraulic design approach would be beneficial could include complex sites (e.g. high embankments, streams with multiple culvert barriers), steel pipe culverts, or sites with threatened fish populations. This approach could potentially be separate to the generalised design criteria and methodology for box culverts (to be developed in Y2 of this project), or could be included in the future proposed methodology as an option for situations where it is thought design using generalised criteria will not produce the best outcome.

4 KEY FINDINGS AND RECOMMENDATIONS

4.1 INTERPRETATION OF KEY FINDINGS

This report has detailed a review of the literature relating to fish biological factors and potential constraints to fish passage caused by typical culverts. A range of topics relating to fish migration have been examined, including migratory behaviours, seasonality, regionality and triggers for migration. The swimming ability of Queensland fish has also been examined, along with certain swimming behaviours which may contribute to fish passage success. Knowledge gaps and further research requirements relating to these topics are also identified and discussed.

Culvert constraints to fish passage have been examined, including water velocities, turbulence, depths, temperature, light contrasts and vertical barriers. A review of state guidelines has also been completed with the aim of establishing current culvert fish passage practice in each jurisdiction. The NZ guidelines have also been considered in this review, and some US guidelines have been briefly examined, but these were not reviewed in detail.

From this literature review, there are a range of conclusions that can be drawn with respect to the definition of functional requirements for fish passage in Queensland. These are presented in the following subsections. When considering these conclusions, it must be noted that much of the data available which relates to fish migrations and passage through culverts and other in-stream structures in Queensland exists either as part of limited quantitative data, or more commonly as informal observations or anecdotal evidence. Furthermore, the literature reviewed was limited to what was available through conventional literature searching, meaning that unpublished documents could not be captured. It is reported that much of the work that contributed to the development of the current Queensland ADR was not published, meaning that it could not be captured in this review. These points mean that it is hard to make definitive conclusions in many cases, and knowledge gaps are highlighted where necessary.

4.1.1 FISH MIGRATION CHARACTERISTICS

Fish can generally be placed into one of several broad migratory classifications, which are defined based on the regionality of the migratory event, the life cycle stage that the fish migrates during, and the purpose of the migration. These classifications include:

- anadromous (migrate upstream to freshwater from saltwater habitat as juveniles and adults post-spawning)
- catadromous (migrate upstream to freshwater habitat as adults pre-spawning)
- potamodromous (migrate wholly within freshwater habitat for either facultative or non-obligate reasons)
- amphidromous (migrate between saltwater and freshwater for non-obligate reasons).

These broad classifications can be further subdivided into juvenile and adult upstream and downstream phases, for example: migrates upstream from marine environment while juvenile (JUD). Most Queensland species can be placed into one of these established migratory categories, but not all species have had their movement patterns comprehensively quantified. It can generally be assumed that at least some fish will be moving whenever there is connectivity in a stream, although movement is likely to be reduced in the winter months.

Most studies to date which have provided formal observations of fish movement have been focused on fishway effectiveness rather than directly on the migratory biology of fishes, with observations of fish movement made by observing which fish are ascending or descending the fishway, often accompanied by data pertaining to the timing of the movement and measurements of river discharge. This is supplemented by informal observations made in the field for some species which have been collated and referenced to by publications such as *Freshwater Fishes of North-Eastern Australia* (Pusey, Kennard & Arthington 2004).

Some movement phases are more critical to the life cycle of fishes (i.e. spawning migrations and dispersal), but facultative movements for purposes such as finding food or avoiding predators should not be excluded from considerations when defining the range of flows over which a culvert needs to support fish passage. This means that culverts need to be designed to provide fish passage during flows where defined migratory events are occurring, as well as at smaller base flows where fish might be moving for facultative purposes. The flow ranges over which fish might need to attempt passage have not been clearly defined however, and it may be the case that different ranges of flows need to be considered depending on the hydrology and fish populations present in different catchments, or more broadly, different regions in Queensland. This is a key knowledge gap, and further work with the aim of identifying fish passage design flow ranges for Queensland would likely assist in the definition of design criteria for fish passage.

Increasing stream flows are widely considered to be a trigger for the commencement of fish migration efforts, but there is some uncertainty around the exact range of discharge conditions under which fish will be attempting upstream migration. Some authors have postulated that fish are most likely to be attempting migration during the lag time of rainfall events and are less likely to be attempting migration during peak stream flow conditions. This does not appear to be backed up by significant research outcomes from Queensland or Australia, although it has been anecdotally confirmed by fish passage experts who were contacted as part of the review presented here. It would be beneficial to conduct field investigation with the aim of verifying the timing of fish movement during rainfall events, but health and safety requirements may limit the scope of observation depending on site conditions.

Other migratory triggers include changes in temperature, increased photoperiod, and the reaching of a certain stage of maturity. Some of these factors may be interlinked with the start of the wet season which is characterised by increases in rainfall and streamflow activity. This connection has not been comprehensively investigated however, and this assumption may not apply to all fishes. Furthermore, it has been reported that fish which are native to temperate areas are more likely to react to changes in water temperature and photoperiod, while tropical fish are most likely to react to rising water levels as a stimulus for migration.

There are some obvious distinctions which can be made for the split between catchments in coastal Queensland and inland catchments west of the Great Dividing Range, primarily that only potamodromous species can be found west of the Range. Inland species are likely to migrate in response to increased flow, and since western inland systems may flow at high rates for extended periods of time fish may need to migrate through culverts during these high flow conditions. This contrasts with eastern coastal systems which generally experience flood flows for a lower duration, meaning that fish migrating in response to increased flow are more likely to either be able to gain passage after culvert drownout occurs, or be able to tolerate a period of delay until discharge reduces to a level under which passage is possible.

Much of the information available relating to migratory behaviour for Queensland fish species is based on informal field observations and personal communication from fish biologists and others who have observed fish behaviour in the field. As has been noted, these observations are commonly associated with the installation of fishways, although there has been some limited observation of culverts acting as a barrier to small-bodied species after increased flow events. Further monitoring of both plain culverts and culverts designed using the current ADR is recommended to establish the effectiveness of the current remediation and design options for fish passage.

There is some literature available that details the spatial distribution of Queensland fish species and the catchments that fish have been observed in, particularly the publications *Freshwater Fishes of North-Eastern Australia* (Pusey, Kennard & Arthington 2004) and *Freshwater Fishes of Northern Australia* (Pusey et al. 2017). The data within these publications is not necessarily comprehensive, and in some cases assumptions may need to be made where assessing smaller catchments or those which are otherwise not covered in these publications.

4.1.2 FISH BIOLOGY CHARACTERISTICS

Swimming ability

Studies have shown that fish swimming ability is often closely linked to fish size, although there are also some connections to body shape and other external factors such as typical habitat and migratory strategy. One researcher has developed a statistical prediction tool for swimming based on fish characteristics (Watson et al. 2019), but since this has been developed based on laboratory swimming ability, the predictions may be conservative.

Review of the literature has shown that Australian studies of fish swimming ability have primarily been completed under laboratory conditions which involves the use of rectangular flumes or open swim tunnels. These apparatuses are generally constructed from smooth materials (e.g. PVC), and have smaller dimensions compared to typical culverts. Rectangular flumes are geometrically similar to box culverts, but since flumes are generally narrower than typical box culverts, the hydraulic conditions generated within flumes may not be representative of the conditions that may develop in a wider box culvert cell, particularly when baffles are installed. Most culverts are either precast concrete or corrugated metal, which have a higher level of roughness than the laboratory testing equipment (i.e. higher Manning's roughness). Higher roughness results in a greater boundary layer effect and lower velocities in the vicinity of the culvert surface which may be exploited by fish. The influence of this roughness effect on fish passage success is not captured by swim studies which use smooth equipment.

In the field, fish which are attempting passage may respond to various stimuli (e.g. biological urge to migrate, schooling effects, flow conditions), which are very hard to replicate in a laboratory scenario. This means that indications of swimming capability determined during laboratory testing may be conservative, and this has been recognised by several researchers. While this may be the case, it is unlikely that swimming capability has been underestimated by orders of magnitude, particularly for small-bodied and juvenile fishes. This means that for flows where small-bodied and juvenile fish are attempting passage, it is unlikely that water velocities within a defined RVZ could be significantly above 0.3 m/s, although the exact velocity that fish are able to gain passage against is unclear in many cases.

The most comprehensive laboratory fish passage study to date in Australia was conducted by Watson et al. (2019) who determined critical and sprint swimming speeds as well as culvert traversability for 21 species of fish commonly found in NSW. There was some crossover with Queensland species, but the bulk of key species identified in Appendix A have not been tested. The 0.3 m/s maximum velocity guideline was reasonably well supported by the estimation of swimming ability and culvert traversability, with only four species at the fish life stage and body size tested expected to be unable to traverse an 8 m culvert against an average velocity of 0.3 m/s.

It must be recognised however, that 8 m is a relatively short culvert length, and the average TMR culvert is closer to 15 m in length. At this length, the number of species which would be unable to gain passage against 0.3 m/s velocity increases to eight. This indicates that some form of baffle system is required which provides near-zero velocity rest areas to support passage of these fish through culverts which are of an average length or greater. The Watson et al. (2019) study was focused on juvenile and small-bodied species, but it is unclear how well the results can be extrapolated to other species and life cycle stages other than those tested. Critically, most fish tested were larger than the sizes of fish indicated by the 'first important life cycle stage' specified in Table A.1, Appendix A, and it is unclear whether the results could be applied to these smaller fish, or whether fish need to migrate at this earlier life stage.

Most of the testing in Australia has been done in rectangular flumes, meaning that the conditions that are created within pipe culverts have not been adequately represented. In pipe culverts, boundary layers (i.e. RVZs) are generated close to the water surface on the wetted perimeter of the culvert barrel. Personal communication from T. Marsden indicated that fish are likely to exploit these RVZs in a pipe culvert, but there does not seem to have been any Queensland or Australian studies which have formally verified this observation. The extent to which fish can exploit pipe culvert RVZs is likely to be a key factor in the

development of criteria for pipe culvert rehabilitation, and further investigation of this may be warranted, particularly for small-bodied fish.

Swimming behaviours

Rheotactic response is a key element of fish behaviour which defines how fish react to water flows and turbulence. If there is not sufficient attraction flow at the entrance to a culvert, fish may not attempt passage. This highlights the importance of considering fish passage requirements under base flow conditions, which is set according to the expected movement behaviour of fish at a site.

Station holding is a specialised behaviour which is displayed by several smaller-bodied fish species, typically gudgeons and galaxiids in Australia. These fish can grasp rough substrates and hold position against flows up to a certain magnitude, which allows the fish to rest and regain energy in between periods of swimming at burst speed (U_{sprint}) or critical speed (U_{crit}). Station holding behaviour has not been quantified by laboratory swimming studies, since flumes are generally constructed from smooth materials. A field study which focuses on passage of gudgeons through typical culverts under a range of natural flow and velocity conditions would assist in determining the benefit that these fish can derive from station holding.

4.1.3 CULVERT CONSTRAINTS FOR FISH PASSAGE

Culverts are widely recognised by the literature as barriers to upstream passage by Queensland and Australian fish species. Known barriers presented by culverts include excessive velocities, excessive turbulence, shallow water depths, light contrasts, and vertical barriers. There have been anecdotal accounts recorded for a wide range of Queensland species which indicate that culverts and other road crossings act as barriers to movement, but the prevailing flow conditions at the times that the observations have been made are often unclear.

Excessive velocity

There is significant variance in the literature regarding the thresholds at which culvert conditions begin to present an unacceptable barrier to fish passage. Much of this can be attributed to the fact that there is significant variance in the abilities and behaviours of migrating fishes. Generally, it will be prudent to consider the abilities of the weakest fish which will be attempting passage when defining a barrier.

The figure of 0.3 m/s for maximum velocity through culvert barrels was developed based on limited research and appears to have been initially based on the swimming ability of three fish species at a fishway in the southern Murray-Darling Basin. Recent research by Watson et al. (2019) has provided support for the figure of 0.3 m/s, with some caveats as discussed in Section 4.1.2. It is generally accepted that limiting water velocity within culvert RVZs to this maximum velocity will support the passage of most juvenile and small-bodied fishes.

It is widely accepted that juvenile and small-bodied fish are relatively weak swimmers, and therefore are less capable of gaining passage against elevated culvert velocities. To a degree, this also means that small-bodied fish will not be attempting migration during flow events where natural streamflow velocity conditions are prohibitive. This is reflected by the advice of the Victorian fish passage guidelines, which state that small-bodied fish (20–120 mm) are most likely to be moving during low and rising flows in spring and summer.

Some researchers have observed that certain species of small-bodied fish (often gudgeons) are able to use station holding to gain passage against water velocities which would otherwise prevent passage. Station holding refers to the ability of some typically small-bodied fish species to grasp the substrate and rest until they regain sufficient energy to continue swimming. Some weaker fishes are also able to seek out RVZs in natural channels. This behaviour has been observed in a laboratory setting, where fish have been observed to seek out RVZs in a flume test channel by spending the majority of time swimming in the bottom corners of the rectangular flume.

Turbulence

Excessive turbulence may disorientate fish and lead to fish orienting themselves downstream. Once this happens fish are likely to be washed downstream and will need to attempt passage again. In contrast to this, certain fish can derive a benefit from turbulence, using it to propel themselves forward. Generally, the size of turbulent eddies must be similar to the size of the fish attempting passage if the fish is to take advantage of the turbulence. The turbulence generated by the ADR baffle setup was investigated during development, which led to the current 150 mm baffle width. Modelling of turbulence is very complicated and may not be possible with conventional CFD analysis. Considering this, it is likely best to target the minimisation of turbulence and position turbulent eddies away from where fish are likely to be attempting to swim or rest.

Water depth

Water depth is a key consideration particularly for larger bodied fish which may be unable to successfully pass a structure if water depth is lower than in the adjoining channel. This may be an issue for wide multi-cell installations under low flow conditions, although embedment of the low flow channel may counteract the issue in these circumstances.

Light contrasts

The dark conditions within typical culverts during the daytime may be a behavioural barrier for certain species of fish. It is unclear whether this is likely to impact upon swimming ability once a fish enters a culvert, but certain species may avoid darkened culverts altogether, although research has been limited to laboratory studies. Further field observation of fish which have shown avoidance behaviour in the laboratory is likely to be required to establish the scope of the darkness avoidance behaviour and determine whether it can be overcome by factors such as the biological need for fish to migrate.

Vertical barriers

Vertical barriers are a critical issue for Australian fish which have very limited jumping ability. A drop of 100 mm is enough to stop passage to practically all Australian species, which makes the elimination of vertical barriers of the utmost importance to support passage outcomes. Further research in this area is unlikely to yield evidence of improved tolerance to vertical barriers compared to current knowledge.

Water temperature

Water temperature may potentially factor in the swimming ability of fish attempting migration, and it has shown that swimming ability significantly reduces in a laboratory setting as temperature reduces. Fish will generally be migrating under favourable temperature conditions, but there are some Queensland species such as lungfish which migrate during periods of reduced temperature. Further research in this regard may be beneficial particularly in situations where environmental discharges from dams are likely.

4.1.4 REMEDIATION OPTIONS

There are various baffle options available which are designed to enhance the low-velocity boundary layer on the sidewalls or invert of culverts and/or provide low-velocity resting areas for fish which are attempting passage. Baffles are generally identified as improving fish passage outcomes at least to some degree, but the degrees of success which have been observed for different baffle designs have been variable.

There has been some monitoring of fishway remediation success in Queensland, but formal monitoring of remediated and new 'fish-friendly' culvert installations appears to have been very limited. There does not appear to have been a significant pre-implementation field study or post-implementation investigation of the effectiveness of the current full-height rectangular baffle solution which is prescribed by the ADR. There have been some limited field observations which have indicated that the baffles do support some measure of passage by small-bodied fishes. One limited field study indicated that the prescribed configuration did improve fish passage outcomes, but this was for a 4 m length of baffled culvert, which is significantly shorter than a typical culvert. It is reported that some testing was carried out as part of the development of the

prescribed baffle system, but since this was not written up and published the details of the testing could not be reviewed.

There exist various other baffle options which have been implemented within box and pipe culverts with varying degrees of success. Baffles have generally been proven to improve fish passage outcomes where implemented, although it is not unforeseen for baffle installation to result in unintended consequences, such as obstruction of fish passage. In most cases, field monitoring of proposed baffle setups during flows where fish passage is required would be beneficial in identifying whether baffle options are appropriate.

The installation of a tailwater weir and rock ramp fishway which backwaters a culvert to reduce barrel velocities has shown to be an effective remediation option for a 70 m long culvert in Victoria, but it has been indicated by TMR that such an installation may not fit within typical road reserve width. This may limit its use in most situations, but it may be appropriate for certain sites where a sufficient reserve width can be provided. Under low flow conditions, standing water generated by a tailwater weir installation may result in a lack of rheotactic response from fishes at base flow conditions, leading to reduced passage outcomes. Standing water may also be a health risk in areas where mosquito breeding is an issue. In conclusion, the tailwater weir and fishway option has been shown to improve passage outcomes in one field study, but its use may be limited to specialised sites and/or further investigation and development may be required.

4.1.5 EXISTING FISH PASSAGE GUIDELINES

Fish passage requirements and guidelines from several states and overseas have been reviewed, including NSW, Victoria, South Australia, and New Zealand. Generally, guidelines from interstate and overseas are less prescriptive compared to the Queensland guidelines regarding the solutions (e.g. different types of baffles) which can be adopted to provide fish passage at culverts. Despite this, most guidelines provide some measure of prescriptive design criteria which must be met to demonstrate fish passage compliance. Departure from these criteria needs to be backed up by proof of suitability relating to fish swimming ability and expected migratory flows.

The current legislative framework in Queensland allows for this approach through the development application process, but since the functional requirements for fish are not well defined, the default criteria are typically relied upon. It is possible that similar outcomes are realised in other states, since detailed functional requirements for fish passage do not appear to have been well defined for any significant portion of Australian fishes.

The figure of 0.3 m/s maximum velocity for fish passage is common between the fish passage guidelines for NSW and Victoria, and the Queensland ADR. The Queensland requirement is to provide a contiguous 0.3 m/s velocity in a 100 mm wide RVZ along the bankside wall of a culvert. It is unclear how the 0.3 m/s velocity is to be provided in the NSW and Victorian guidelines, although it could be loosely assumed that the velocity is considered as an average cell velocity. Since fish are known to target RVZs when attempting passage, the configuration of the Queensland requirement appears to be reasonable from both a fish passage perspective and a hydraulics perspective.

There is no specific guidance on the range of flow conditions that the 0.3 m/s maximum velocity must be achieved for in the Victorian guidelines, and the Queensland requirements are to provide fish passage for all fish attempting to move through a culvert up to drownout, which is currently interpreted as a requirement to provide a contiguous 0.3 m/s RVZ for all flows up to drownout. The NSW guidelines specify that the 0.3 m/s culvert cell velocity needs to be achieved for flows up to 0.5 m deep within the culvert barrel, but it is unclear whether this was based on any significant research outcomes, and therefore further work would be required to establish whether it would be appropriate to apply a similar approach in Queensland.

In NZ, minimum design criteria are specified for hydraulic design, although provision is made to consider the swimming ability of target fish species when setting average culvert velocities. Since only one species of fish has been comprehensively studied in NZ with regard to swimming ability (common galaxias), the swimming ability of this fish is typically used by default when designing for allowable culvert velocity. The common galaxias is a relatively weak-swimming fish, and it appears that the culvert barrel velocity requirements for

new culverts which are based on the swimming ability of the common galaxias are more onerous than those which are currently applied in Queensland. This is likely due to the policy of not using baffles which is recommended by the guidelines, but the method in which the guidelines are typically applied is unclear.

Recommended high (20% exceedance flow) and low (95% exceedance flow) fish passage design flows are specified by the NZ guidelines. This approach is not taken by any of the Australian guidelines, but similar design flow ranges are specified by some US state guidelines which are based on migratory behaviour of local fish species. The NZ fish passage design flows are provided as a rule of thumb based on NZ conditions and the basis upon which the limits were developed is unclear. Further work would be required to determine high and low fish passage flows which are appropriate for Queensland conditions. The fish passage design flow range may vary for different regions and stream flow characteristics which could include ephemeral vs perennial streams, or coastal vs. inland catchments. Monitoring of fish movement matched to flow measurement is likely to be an appropriate means of establishing a range of fish passage flows, with determination of flows where fish are not attempting passage being a key outcome.

4.2 SUMMARY OF THE GAPS IN THE RESEARCH

From the review many gaps in the research were identified. These are discussed in Section 3, and a summary of key gaps are made here. The research gaps are divided into separate areas as appropriate.

4.2.1 FIELD MONITORING

Overall, the literature review identified there is a general lack of monitoring and documentation of fish passage under field conditions. Specifically:

- performance of existing structures
- proportional fish passage success through existing structures
- impacts of baffles and other remediation measures on the hydraulic performance of culverts.

4.2.2 FISH MIGRATION

- Migratory behaviour of facultative migrators, including the flow conditions that these fish migrate during and the migratory triggers that they respond to are poorly understood.
- The behaviour of species which attempt to migrate upstream during periods of reduced temperature (i.e. late autumn, winter, early spring) are not well understood, and it is unclear whether the low temperatures are detrimental to swimming ability for these species.
- It is unclear whether there are significant numbers of streams in Queensland for which environmental flow releases (with reduced water temperatures) from dams trigger key fish migration events.
 - There may be a need for reduced culvert water velocities or tailored remediation techniques where passage under reduced temperature is required.

4.2.3 SWIMMING ABILITY AND BEHAVIOURS

- Laboratory swimming ability tests have been conducted on a limited selection of the key Queensland species identified by Appendix A.
- The statistical swimming ability prediction method developed by Watson et al. (2019) showed good results for the species tested, but further testing is required to verify its robustness.
 - This could be achieved by predicting the swimming ability of some key untested Queensland species and checking whether the results are accurate.
 - Verification could be achieved through laboratory testing of key species or field observations.
- Swimming ability data determined in the laboratory may be conservative compared to field swimming performance, but this has not been formally quantified.

- A controlled field setup would be required to achieve this, which could somewhat reduce the viability of the results as true field measurements.
- The impact on passage success of station holding behaviour in the field is not well understood. It would be ideal to understand this effect for a range of substrate types including natural substrate, artificial substrate used for roughening, bare concrete and corrugated metal.
 - Whether station holding could improve the passage success of weak-swimming species such as gudgeons could be determined.
- It is unclear whether rheotactic response and/or migratory urges are able to reliably overcome darkness avoidance behaviour in the field which has been exhibited by certain diurnal species in a laboratory setting.

4.2.4 CULVERT CONSTRAINTS FOR FISH PASSAGE

- The suitability of box culvert baffle configurations as recommended by Witheridge (2020) has not yet been assessed.
 - Baffle options could potentially be incorporated into future box culvert design specifications.
- Velocity conditions within concrete and corrugated metal pipe culverts (including development of RVZs) have not been comprehensively reviewed in Australia, although there may be some relevant overseas research which was out of scope of the current project.
 - Potential methods of fish passage and how fish passage outcomes may be enhanced could be considered.
- There are various baffle options specified for pipe culverts in interstate and overseas practice, but it is unclear whether these are appropriate for application in Queensland. Hydraulic and fish passage testing would be required to establish the viability of these baffle options.
- The viability of tailwater weir and fishway combinations for fish passage remediation, particularly as an option for pipe culverts, has not been comprehensively assessed.
- There are a range of alternative baffle options which have been proposed for box culverts. Hydraulic and fish passage testing would be required before these could be considered as an alternative to the current baffle configuration specified by the ADR.

4.3 RECOMMENDATIONS FOR FURTHER WORK

4.3.1 INTERNAL ACTIVITIES

Based on the findings of the review of the literature and the research gaps found, it is recommended that TMR:

- Develop design criteria and methodology for box culverts where fish passage is required. This would be targeted to integrate fish passage assessment into existing TMR drainage structure assessment, and it is recommended to incorporate as a minimum:
 - Specified maximum velocity of 0.3 m/s for passage of small-bodied fish.
 - This should exist in a contiguous RVZ along the wall of a box culvert, or at the intersection of the culvert wall and base.
 - The height and width of this RVZ should be set to completely encompass the size of the fishes that will rely on it to gain passage.
 - Specification of discharge magnitudes for which the maximum velocity must be achieved, with consideration of culvert size, slope and tailwater conditions.
 - TMR to collaborate with DAF to determine appropriate discharge magnitude limits. Further research may be required.

- Provision of appropriate surface roughening or natural substrate along the base of the culvert to facilitate station holding behaviour.
- A selection of remediation options for box culverts, with outcomes from the ongoing trial of fish baffle treatments in box culverts included.
 - Remediation options for pipe culverts should also be included, but further development is required.
- Collaborate with DAF to achieve the specification of an ‘acceptable delay’ method whereby a fish passage culvert will be considered acceptable if it can be shown that:
 - drownout of the culvert occurs within a matter of hours (or other reasonable period of delay based on site-specific fish biology) and passage over the top of the culvert is considered unrestricted
 - impassable flows last for a matter of hours before reducing to a magnitude where fish are able to gain passage against velocities generated in the culvert.
- Consider supporting the development of a fish information database for fish passage works. There are some relevant resources available which may serve as a basis (e.g. Appendix B.2.1), but the most efficient approach could be to collect data on a case-by-case basis in situations where investigation of fish characteristics is required. Fish data which is collected and databased could then be applied to future projects where similar species are present.
- Consider the merits of developing a TMR framework for fish passage. This would be complementary to the current SDAP codes and would provide a centralised instrument for TMR fish passage design.
 - The framework could include:
 - outline of legislative requirements
 - decision-making guidance
 - best practice for fish passage
 - generalised design criteria for box and pipe culverts.
- Consider pursuing the implementation of a legislative instrument which can be used to trigger a waterway re-assessment where it is thought that the current waterway classification may be incorrect.
 - This could streamline the process of requesting alternative waterway determinations.

4.3.2 EXTERNAL ACTIVITIES

If in an appropriate position, TMR may also consider supporting external research related to key fish passage knowledge gaps including:

Field monitoring

- Field monitoring of existing culvert structures with and without fish passage design elements to evaluate the success of fish passage and the performance of current fish passage components.
- Field monitoring to evaluate the impact of current waterway barrier works on impeding fish passage and the impact on fish population sustainability across catchments possibly aiming to determine if there are key factors in fish passage that influence population sustainability (maximum delays to passage or number of barriers in a sequence)

Fish migration

- Investigate viability of developing a database of fish migration behaviour for key Queensland species including timing, triggers, life cycle stages, fish maturity/size, numbers of fish migrating and flow conditions. Data collated by Kapitzke may form a basis for this database (Appendix B.2).
 - This data could then be used to develop targeted biological performance requirements for structures such as acceptable delays to passage and acceptable passage success rates.

Fish swimming ability

- Investigation into whether the impact of reduced temperatures on swimming ability needs to be considered in culvert design.
 - This may include investigation of species which migrate during cooler months of the year, and/or investigation of the prevalence and impacts of environmental water releases on fish migration and culvert passage.
 - Better understanding of these factors could improve passage outcomes at sites where fish attempt passage at reduced water temperatures.
- Further investigation of the statistical fish swimming ability prediction tool developed by Watson et al. (2019) to determine its applicability to Queensland fish species.
 - This could be a useful tool to predict site-specific swimming abilities if the species and size classes which will be attempting passage at a site are known.
 - This could potentially allow for the specification of higher maximum culvert velocities at certain sites, but this would be highly site-specific.
- Research to assess whether swimming ability data determined in the laboratory is conservative compared to field swimming performance.
 - This could potentially show that passage is possible against higher culvert velocities (compared to 0.3 m/s) for certain species of fish.
- Investigation of station holding behaviour of weak-swimming small-bodied fish (gudgeons, galaxiids) on common culvert materials and natural substrates.
 - This could enhance understanding of the passage capability of these species which have been observed to struggle against a velocity of 0.3 m/s in the lab.

Culvert barriers and remediation options

- Investigate the suitability of box culvert baffle configurations as recommended by Witheridge (2020).
 - Baffle options could potentially be incorporated into future box culvert design specifications.
- Review velocity conditions within concrete and corrugated metal pipe culverts (including development of RVZs) including interstate and overseas research.
 - Consider potential methods of fish passage and how fish passage outcomes may be enhanced.
- Review baffle options for pipe culverts from interstate and overseas practice.
 - This would aim to assess applicability for use in Queensland.
- Assess the viability of tailwater weir and fishway combinations for fish passage remediation, particularly as an option for pipe culverts.
 - Assess whether a design which fits into common road reserve widths is viable.
 - This could be a cost-effective alternative to pipe jacking or full replacement of pipe culverts.

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APPENDIX A KEY QUEENSLAND FISH SPECIES

Table A.1: Key Queensland fish species identified by T. Marsden in 2019

Common name	Species name	1st important life stage (mm)	2nd important life stage (mm)	3rd important life stage (mm)	Has swimming ability been tested?
River whaler	<i>Carcharhinus leucas</i>	600	1000		N/A
River stingray	<i>Dasyatis fluviorum</i>	400	1000		N/A
Milkfish	<i>Chanos chanos</i>	80	200	500	
Oxeye herring (tarpon)	<i>Megalops cyprinoides</i>	80	150	300	
Giant herring	<i>Elops australis</i>	80	150		
Silver biddy	<i>Gerres filamentosus</i>	40	100		
South Pacific eel*	<i>Anguilla obscura</i>	40	150	300	
Long-finned eel*	<i>Anguilla reinhardtii</i>	40	150	300	
Bony bream	<i>Nematalosa erebi</i>	15	30	100	
Marine bony bream	<i>Nematalosa come</i>	15	30	100	
Forked tail catfish	<i>Arius Sp</i>	75	150	300	
Black catfish	<i>Neosilurus ater</i>	40	100	300	
Hyrtl's tandan	<i>Neosilurus hyrtlii</i>	40	100	300	
Eeltail catfish	<i>Tandanus tandanus</i>	40	100	300	Yes
Rendahl's tandan	<i>Porochilus rendahli</i>	40	100	300	
Snub-nosed garfish	<i>Arrhamphus sclerolepis</i>	50	100		
Long tom	<i>Strongylura krefftii</i>	100	200	400	
Marjorie's hardyhead	<i>Craterocephalus marjoriae</i>	20	40		
Fly-specked hardyhead	<i>Craterocephalus stercusmuscarum</i>	20	40		Yes
Pacific blue-eye	<i>Pseudomugil signifer</i>	15	20		Yes
Eastern rainbowfish	<i>Melanotaenia splendida splendida</i>	15	25	40	
Bullrout	<i>Notesthes robusta</i>	10	20	50	
Barramundi	<i>Lates calcarifer</i>	25	40	300	
Golden perch	<i>Macquaria ambigua</i>	25	40	120	Yes

Common name	Species name	1st important life stage (mm)	2nd important life stage (mm)	3rd important life stage (mm)	Has swimming ability been tested?
Murray cod	<i>Maccullochella peelii peelii</i>	50	600	1000	Yes
Agassizi's chanda perch	<i>Ambassis agassizi</i>	20	40		
Sail-fin perchlet	<i>Ambassis agrammus</i>	20	40		
Olive perchlet	<i>Ambassis nigripinnis</i>	20	40		
Spangled perch	<i>Leiopotherapon unicolor</i>	20	40		Yes
Banded grunter	<i>Amniataba percoides</i>	15	30		
Sooty grunter	<i>Hephaestus fuliginosus</i>	30	100		
Silver perch#	<i>Bidyanus bidyanus</i>	25	40		Yes
Small-headed grunter	<i>Scortum parviceps</i>	25	200		
Jungle perch	<i>Kuhlia rupestris</i>	25	80	150	
Mouth almighty	<i>Glossamia aprion</i>	30			
Mangrove jack	<i>Lutjanus argentimaculatus</i>	25	80		
Common archer fish*	<i>Toxotes chatareus</i>	10	40		
Spotted butterflyfish	<i>Scatophagus argus</i>	20	80		
Striped scat	<i>Selenotoca multifasciata</i>	20	80		
Sea mullet	<i>Mugil cephalus</i>	15	20	40	Yes (Mitchell (1989))
Empire fish	<i>Hypseleotris compressa</i>	10	15	20	Yes
Boofhead carp gudgeon	<i>Hypseleotris spp</i>	20			
Purple-spotted gudgeon	<i>Mogurnda adspersa</i>	20	40		Yes
Big-headed gudgeon	<i>Philypnodon grandiceps</i>	20	40		Yes
Flathead goby	<i>Glossogobius giurus</i>	20	40		
Bug-eyed goby	<i>Redigobius bikolanus</i>	15	40		Yes
Roman-nosed goby	<i>Awaous acritosus</i>	20	40		

Source: Marsden (n.d.).

APPENDIX B FISH DATA

B.1 WORK OF WATSON ET AL. (2019)

Table B.1: Physical and behavioural characteristics of species studied by Watson et al. (2019)

Scientific name	Common name	Common adult size (mm)	Location	Preferred habitat	Migration classification	Movement distance'	Body shape	Tail shape	Depth station	Swimming mode
Trachystoma petardi	Freshwater mullet	400	Coastal	Channel specialist	Catadromous	Macro	Fusiform	Indented	Surface	Sustained
Maccullochella peelii	Murray cod	700	Inland	Channel specialist	Potamodromous	Meso	Compressiform	Rounded	Pelagic	Slow Sustained/ Burst
Macquarie ambigua	Golden perch	500	Inland	Channel specialist	Potamodromous	Macro	Compressiform	Truncate	Pelagic	Slow Sustained/ Burst
Macquarie novemaculeata	Australian bass	400	Coastal	Channel specialist	Catadromous	Macro	Compressiform	Indented	Pelagic	Slow Sustained/ Burst
Bidyanus bidyanus	Silver perch	300	Inland	Channel specialist	Potamodromous	Macro	Compressiform	Indented	Pelagic	Sustained/ Burst
Leiopotherapon unicolor	Spangled perch	300	Inland	Generalist	Potamodromous	Meso	Compressiform	Truncate	Pelagic	Slow Sustained/ Burst
Galaxias brevipinnis	Climbing galaxiid	100	Coastal	Channel specialist	Potamodromous	Meso	Sagitiform	Truncate	Pelagic	Slow Sustained/ Burst
Retropinna semoni	Australian smelt	60	Coastal/ Inland	Generalist	Potamodromous	Micro	Fusiform	Forked	Pelagic	Sustained
Craterocephalus stercusmuscarum	Fly-specked hardyhead	55	Inland	Generalist	Potamodromous	Meso	Fusiform	Indented	Pelagic	Sustained
Pseudomugil signifier	Pacific blue-eye	40	Coastal	Generalist	Amphidromous	Micro	Fusiform	Indented	Pelagic	Sustained

Scientific name	Common name	Common adult size (mm)	Location	Preferred habitat	Migration classification	Movement distance'	Body shape	Tail shape	Depth station	Swimming mode
Melanotaenia fluviatilis	Murray river rainbowfish	85	Inland	Generalist	Potamodromous	Micro	Compressiform	Indented	Pelagic	Slow Sustained/ Burst
Melanotaenia duboulayi	Crimson-spotted rainbowfish	80	Coastal	Generalist	Potamodromous	Micro	Compressiform	Indented	Pelagic	Slow Sustained/ Burst
Rhadinocentrus ornatus	Ornate rainbowfish	40	Coastal	Wetland specialist	Potamodromous	Micro	Fusiform	Indented	Pelagic	Slow Sustained/ Burst
Ambassis agassizii	Olive perchlet	60	Coastal/ Inland	Wetland specialist	Potamodromous	Micro	Compressiform	Forked	Pelagic	Slow Sustained/ Burst
Nannoperca australis	Southern pygmy perch	60	Inland	Wetland specialist	Potamodromous	Micro	Compressiform	Rounded	Pelagic	Burst
Tandanus tandanus	Eel tailed catfish	450	Coastal/ Inland	Generalist	Potamodromous	Meso	Compressiform	Pointed	Benthic	Slow Sustained/ Burst
Hypseleotris compressa	Empire gudgeon	80	Coastal	Generalist	Amphidromous	Mew	Compressiform	Rounded	Benthic	Burst
Hypseleotris galii	Firetail gudgeon	35	Coastal	Generalist	Potamodromous	Micro	Compressiform	Rounded	Benthic	Burst
Philypnodon grandiceps	Flathead gudgeon	80	Coastal/ Inland	Generalist	Potamodromous	Micro	Depressiform	Rounded	Benthic	Burst
Mogurnda adspersa	Purple spotted gudgeon	80	Coastal/ Inland	Generalist	Potamodromous	Meso	Compressiform	Rounded	Benthic	Burst
Redigobius bikolanus	Speckled goby	40	Coastal	Generalist	Amphidromous	Mew	Compressiform	Rounded	Benthic	Burst

Source: Watson et al. (2019).

Table B.2: Measured critical and sprint swimming speeds

Scientific name	Common name	U _{crit} size (cm) (Mean ± SD [range])	U _{crit} 25 th percentile (m/s)	U _{crit} mean (m/s)	U _{crit} (n)	U _{sprint} size (cm) (Mean ± SD [range])	U _{sprint} 25 th percentile (m/s)	U _{sprint} mean (m/s)	U _{sprint} (n)
Macquarie novemaculeata	Australian bass	6.0 ± 0.7 [4.3 - 7.3]	0.53	0.60	31	3.9 ± 0.5 [3.4 - 5.0]	0.52	0.58	25
Retropinna semoni	Australian smelt	4.5 ± 0.7 [2.5 - 6.0]	0.62	0.66	25	4.8 ± 0.7 [3.5 - 6.1]	0.67	0.70	25
Melanotaenia duboulayi	Crimson-spotted rainbowfish	6.8 ± 1.2 [5.3 - 10.3]	0.63	0.63	26	6.8 ± 1.2 [4.6 - 8.5]	0.67	0.70	25
Tandanus tandanus	Eel-tailed catfish	10.0 ± 1.5 [6.1 - 10.7]	0.36	0.41	42	8.3 ± 0.8 [6.9 - 9.4]	0.46	0.50	25
Hypseleotris compressa	Empire gudgeon	5.3 ± 0.7 [4.4 - 7.8]	0.34	0.44	23	5.1 ± 0.8 [4.1 - 6.6]	0.49	0.51	25
Hypseleotris galii	Firetail gudgeon	3.8 ± 0.8 [2.4 - 5.4]	0.34	0.38	25	3.9 ± 0.7 [2.5 - 5.6]	0.48	0.50	25
Philypnodon grandiceps	Flathead gudgeon	4.8 ± 1.0 [3.2 - 6.3]	0.18	0.33	15	5.3 ± 0.6 [3.9 - 5.8]	0.40	0.47	13
Craterocephalus stercusmuscarum	Fly-specked hardyhead	4.6 ± 0.5 [3.7 - 5.8]	0.46	0.49	25	4.8 ± 0.6 [3.8 - 5.9]	0.50	0.55	25
Trachystoma petardi	Freshwater mullet	7.3 ± 1.0 [5.9 - 8.8]	0.80	0.85	14	6.5 ± 1.3 [4.7 - 8.7]	0.82	0.83	17
Galaxias brevipinnis	Climbing galaxiid	9.8 ± 2.4 [8.1 - 11.5]	0.40	0.49	2	NA	NA	NA	NA
Macquaria ambigua	Golden perch	4.7 ± 0.7 [3.5 - 6.4]	0.28	0.32	25	5.5 ± 0.7 [4.2 - 7.5]	0.43	0.47	25
Maccullochella peelii	Murray cod	6.7 ± 1.8 [4.0 - 10.0]	0.40	0.46	43	6.3 ± 1.2 [4.3 - 8.1]	0.57	0.61	40
Melanotaenia fluviatilis	Murray river rainbow fish	7.0 ± 0.6 [6.1 - 8.2]	0.42	0.45	25	6.9 ± 0.5 [6.0 - 7.8]	0.66	0.68	25
Ambassis ambassizii	Olive perchlet	5.8 ± 0.6 [4.5 - 7.0]	0.50	0.53	24	5.6 ± 0.7 [3.5 - 6.5]	0.49	0.57	25
Rhadinocentrus ornatus	Ornate rainbowfish	4.0 ± 0.9 [2.5 - 5.8]	0.46	0.52	25	4.1 ± 0.9 [3.0 - 6.3]	0.45	0.51	25
Pseudomugil signifier	Pacific blue-eye	4.1 ± 0.3 [3.5 - 4.7]	0.42	0.46	25	3.5 ± 0.4 [2.5 - 4.0]	0.48	0.52	25

Scientific name	Common name	U _{crit} size (cm) (Mean ± SD [range])	U _{crit} 25 th percentile (m/s)	U _{crit} mean (m/s)	U _{crit} (n)	U _{sprint} size (cm) (Mean ± SD [range])	U _{sprint} 25 th percentile (m/s)	U _{sprint} mean (m/s)	U _{sprint} (n)
Mogurnda adspersa	Purple spotted gudgeon	6.1 ± 1.8 [4.0 - 10.0]	0.18	0.21	25	7.2 ± 2.2 [4.3 - 10.3]	0.53	0.57	25
Bidyanus bidyanus	Silver perch	6.6 ± 0.8 [0.8 - 8.2]	0.66	0.68	25	8. ± 0.7 [7.4 - 10.1]	0.68	0.74	25
Nannoperca australis	Southern pygmy perch	3.9 ± 0.9 [2.3 - 5.6]	0.34	0.35	25	4.8 ± 0.4 [3.8 - 5.9]	0.44	0.49	25
Leiopotherapon unicolor	Spangled perch	3.6 ± 1.2 [2.5 - 6.7]	0.35	0.41	13	6.3 ± 1.8 [3.0 - 9.5]	0.61	0.66	40
Redigobius bikolanus	Speckled goby	3.2 ± 0.3 [2.6 - 3.8]	0.32	0.34	10	3.0 ± 0.5 [2.3 - 3.8]	0.44	0.43	11

Source: Watson et al. (2019).

Table B.3: Measured endurance and estimated culvert traversal success rate

Scientific name	Common name	V1 size (Mean ± SD [range])	V1 (m/s)	V1 average endurance time (s)	Traverse success rate (%)	V2 (m/s)	V2 average endurance time (s)	V2 traverse success rate (%)	V3 (m/s)	V3 average endurance time (s)
Trachystoma petard'	Freshwater mullet	7.0 ± 1.0 [5.1 - 8.8]	0.5	3600	100	0.6	3033	83	0.7	463
Melanotaenia duboulayi	Crimson spotted rainbow fish	8.8 ± 1.7 [5.5 - 11.3]	0.5	3199	67	0.6	272	86	0.7	117
Bidyanus bidyanus	Silver perch	5.8 ± 0.5 [5.0 - 7.1]	0.5	1332	87	0.6	317	40	0.7	58
Leiopotherapon unicolor	Spangled perch	4.8 ± 1.6 [2.8 - 7.6]	0.5	341	47	0.6	178	10	0.7	49
Retropinna semoni	Australian smelt	5.2 ± 0.6 [3.6 - 6.4]	0.4	3086	67	0.5	2349	47	0.6	134
Maccullochella peelii	Murray cod	1.5 ± 1.2 [5.7- 11.41]	0.4	2952	80	0.5	181	40	0.6	87
Macquarie novemaculeata	Australian bass	6.5 ± 0.7 [5.3 - 8.1]	0.4	2223	80	0.5	242	73	0.6	137
Tandanus tandanus	Eel-tailed catfish	3.1 ± 1.8 [5.1- 11.5]	0.4	1495	7	0.5	1021	27	0.6	41

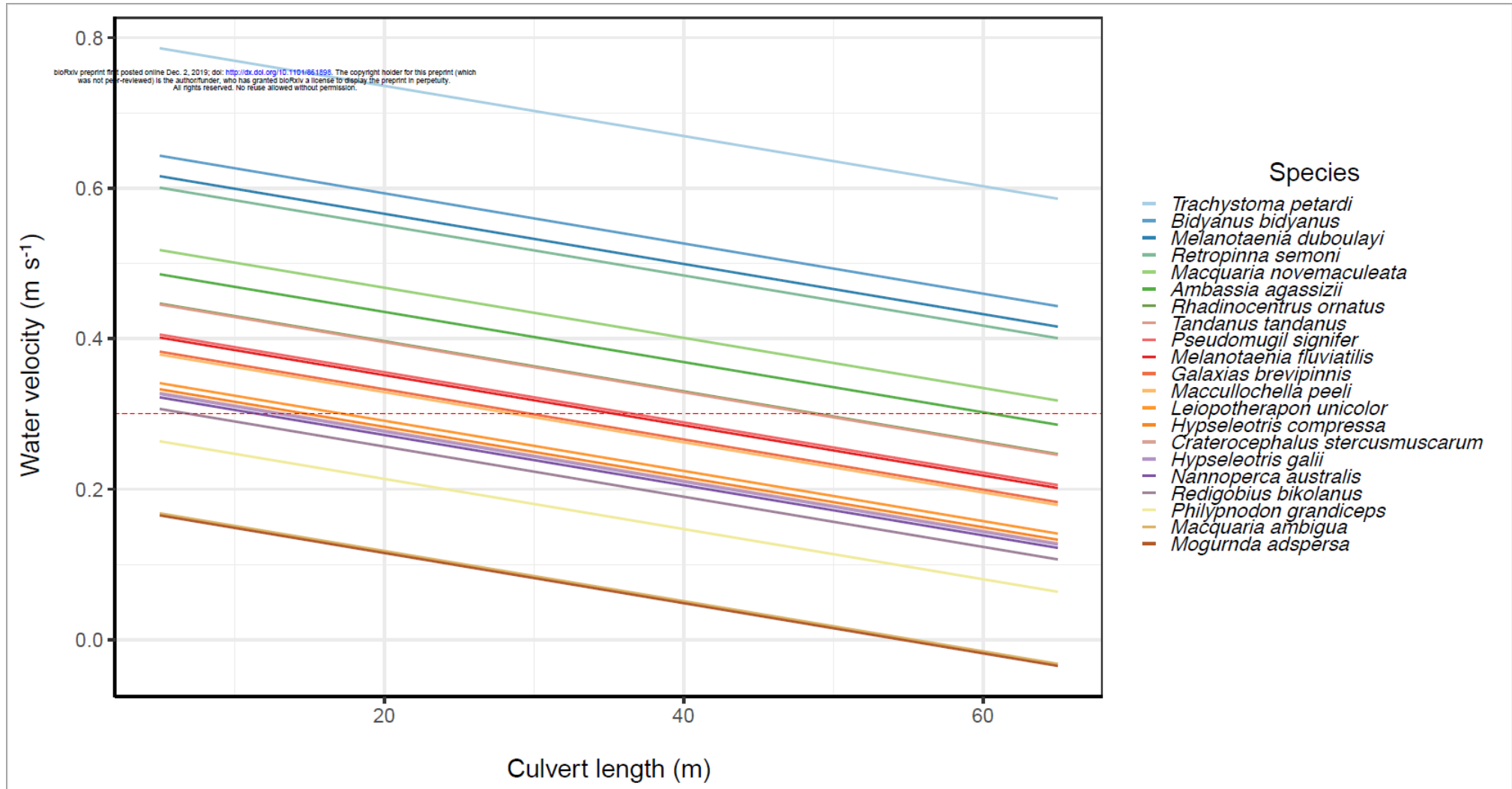
Scientific name	Common name	V1 size (Mean $\pm$ SD [range])	V1 (m/s)	V1 average endurance time (s)	Traverse success rate (%)	V2 (m/s)	V2 average endurance time (s)	V2 traverse success rate (%)	V3 (m/s)	V3 average endurance time (s)
Mogurnda adspersa	Purple spotted gudgeon	8.5 $\pm$ 1.0 [6.4 - 10.3]	0.4	172	40	0.5	101	30	0.6	46
Ambassis agassizii	Olive perchlet	58 $\pm$ 0.5 [4.5 - 6.9]	0.3	3600	93	0.4	1595	20	0.5	319
Craterocephalus stercusmuscarum	Fly-specked hardyhead	5D $\pm$ 0.5 [3.7 - 5.9]	0.3	3159	80	0.4	969	29	0.5	115
Pseudomugil signifier	Pacific blue eyes	3.9 $\pm$ 0.3 [3.1 - 4.5]	0.3	2824	73	0.4	186	7	0.5	86
Nannoperca australis	Southern pygmy perch	48 $\pm$ 0.6 [3.7 - 5.5]	0.2	998	67	0.3	364	47	0.5	76
Macquarie ambigua	Golden perch	53 $\pm$.07 [4.0 - 7.2]	0.2	213	86	0.3	231	46	0.4	133
Hypseleotris compressa°	Empire gudgeon	53 $\pm$ 0.7 [4.2 - 7.9]	0.2	238	NA	0.3	113	NA	0.4	71

Source: Watson et al. (2019).

B.1.1 PREDICTED CULVERT TRAVERSABILITY

Fish are listed in order of their appearance on the plot. The traversability estimates in this plot are based on fish swimming at critical speed with no resting areas provided, i.e. fish must swim through the culvert in a single effort.

Figure B.1 Estimated culvert traversability based on length and water velocity



Source: Watson et al. (2019)

B.2 KAPITZKE (2010B)

B.2.1 FISH MOVEMENT CAPABILITY FOR TULLY-MURRAY CATCHMENT

Table B.4: Fish movement capability groupings for Tully-Murray fish community – upstream movement

Common name (fish movement group)	Family, genus, species	Common length of fish	Flow condition/ migration timing	Fish movement capability
AUS – Adult upstream spawning migration (fish movement groups P1, P3)				
Medium size fish species – adults				
Group AUS1 – Eel-tailed catfish, 15 – 25 cm common adult length				
Black catfish (P1)	<i>Neosilurus ater</i>	Adults 25 cm	Flood flow	- Black catfish, Hyrtl's tandan: inhabits still to slow flowing habitats but capable of negotiating substantial flow velocities - Rendahl's tandan: prefers still to slow flowing habitats
Hyrtl's tandan (P1)	<i>Neosilurus hyrtlii</i>	Adults 20 cm	Flood flow	
Rendahl's tandan (P1)	<i>Porochilus rendahli</i>	Adults 15 cm	Low flow/flood flow	
Group AUS2 – Grunters, 15 – 25 cm common adult length				
Khaki grunter/Khaki bream/Tully grunter (P1)	<i>Hephaestus tulliniensis</i>	Adults 20 cm	Low flow/flood flow	- Sooty grunter: burst speed of TL 20 mm juveniles = 30 BL/s; prolonged speed of TL 20 mm juveniles = 0.28 m/s for 15 min; juvenile fish capable of 7 km / day (average 0.08 m/s) - Spangled perch: fast moving fish capable of 9 km/day (average 0.10 m/s); juvenile fish traveling average 2.7 km/h over 6 hr period, (sustained speed = 0.75 m/s)
Sooty grunter/Black bream (P1)	<i>Hephaestus fuliginosus</i>	Adults 25 cm	Low flow/flood flow	
Spangled perch (P1)	<i>Leiopotherapon unicolor</i>	Adults 15 cm	Low flow/flood flow	

Common name (fish movement group)	Family, genus, species	Common length of fish	Flow condition/ migration timing	Fish movement capability
Small size fish species – adults				
Group AUS3 – Rainbowfish, < 10 cm common adult length				
Eastern Qld rainbowfish (P3)	Melanotaenia splendida	Adults 8 cm	Low flow	Eastern Qld rainbowfish: prefers low velocity habitats
JUD – Juvenile upstream dispersal migration (fish movement groups C1, C2, P2, P3, P4)				
Medium – large size fish species – juveniles				
Group JUD1 – Eels, 60–100 cm common adult length				
Long finned eel (C1)	Anguilla reinhardtii	Adults 100 cm	Flood flow	Long finned eel: maximum swimming speed for juveniles (50 mm length), prolonged speed = 0.3 m/s; burst speed = 0.75 m/s; can climb natural and artificial obstacles (waterfalls, weirs); will move over damp ground to bypass obstacles
Pacific short finned eel (C1)	Anguilla obscura	Adults 60 cm	?	
Group JUD2 – Giant herring/sea bass, 50–120 cm common adult length				
Tarpon, ox-eye herring (C1)	Megalops cyprinoids	Adults 50 cm	Flood flow	Barramundi: NV95 = 0.66 m/s burst speed for juveniles (43 mm length) ; juvenile fish (200 mm length) burst speed = 1.4 m/s; juvenile fish (200 - 300 mm length) prolonged speed = 0.4 m/s for 15 min; juvenile fish (150 - 500 mm length) unable to negotiate 3 m/s
Barramundi (C1)	Lates calcarifer	Adults 120 cm	Flood flow; movement occurs day and night	
Group JUD3 – Flagtails / herring, 20–25 cm common adult length				
Jungle perch (C1)	Kuhlia rupestris	Adults 25 cm	Flood flow	- Jungle perch: prolonged speed of TL 70 mm juvenile = 1 m/s for 15 min - Bony bream: may be found in low velocity or fast flowing habitats
Bony bream (P3)	Nematolosa erebi	Adults 20 cm	Low flow/flood flow; movement at day, limited at night	

Common name (fish movement group)	Family, genus, species	Common length of fish	Flow condition/ migration timing	Fish movement capability
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Small size fish species – juveniles

Group JUD4 – Hardyheads/miscellaneous species, < 20 cm common adult length

Fly specked hardyhead (P4)	<i>Craterocephalus stercusmuscarum</i>	Adults 6 cm	Low flow	- Fly specked hardyhead: prefers low velocity - Bullrout: capable of short bursts of speed when alarmed, but typically moves slowly
Bullrout / freshwater stonefish (C1)	<i>Notesthes robusta</i>	Adults 20 cm	Low flow; apparently prefers to migrate at night	

Group JUD5 – Gobies/Grunters/Gudgeons, 10–20 cm common adult length

False celebes goby (C2)	<i>Glossogobius sp.1</i>	Adults 10 cm	?	- False celebes goby: prefers moderately flowing waters - Roman nosed goby: prefers moderately flowing waters; powerful swimming ability of limited duration
Roman nosed goby (P2)	<i>Awaous acritosus</i>	Adults 10 cm	?	
Banded grunter (P2)	<i>Amniataba percoides</i>	Adults 12 cm	Low flow	
Greenback gauvina (C2)	<i>Bunaka gyrinoides</i>	Adults 15 cm	?	

Source: Kapitzke (2006).

Table B.5: Fish movement capability groupings for Tully-Murray fish community – upstream movement

Common name (fish movement group)	Family, genus, species	Common length of fish	Flow condition/ migration timing	Fish movement capability
Northern trout gudgeon (P3)	<i>Mogurnda mogurnda</i>	Adults 10 cm	?	- Banded grunter: juvenile fish capable of 7 km/day (average 0.08 m/s), with adults moving at 9 km/day (average 0.10 m/s) - Greenback gauvina, Snakehead gudgeon: prefers low velocity habitats - Northern trout gudgeon: prefers low velocity habitats; capable of negotiating cascades and waterfalls
Snakehead gudgeon (C2)	<i>Giurus margaritacea</i>	Adults 17 cm	flood flow	
Group JUD6 – Cardinalfishes/Glass perchlets/Gobies/Gudgeon, < 10 cm common adult length				
Mouth almighty (P3)	<i>Glossamia aprion</i>	Adults 8 cm	Low flow/flood flow	- Mouth almighty: prefers low velocity habitats - Agassiz's glass perch: difficulty negotiating high velocities and turbulent flow conditions - Sailfin perchlet/Glass perch: slow moving fish capable of 5 km/day (average 0.06 m/s) - Pacific mangrove goby, Speckled goby: prefers still to slow flowing waters - Brown gudgeon, Ebony gudgeon, Fire tailed gudgeon, Midgley's carp gudgeon: prefer low velocity habitats - Empire gudgeon: limited swimming capacity, particularly for prolonged speed; capable of moving about 30 km in 3 days
Agassiz's glass perch (P3)	<i>Ambassis agassizii</i>	Adults 5 cm	Low flow/flood flow	
Flag-tailed glassfish (C2)	<i>Ambassi miops</i>	Adults 6 cm	?	
Northwest glassfish (P3)	<i>Ambassis sp.(cf mulleri)</i>	Adults 5 cm	Low flow/flood flow	
Sailfin perchlet/Glass perch (P2)	<i>Ambassis agrammus</i>	Adults 5 cm	Low flow/flood flow; mass upstream migrations in dusk and dawn hours	
Pacific mangrove goby (C2)	<i>Mugilogobius notospilus</i>	Adults 3 cm	?	
Speckled goby (P3)	<i>Rediogobius bikolanus</i>	Adults 3 cm	?	
Tully River goby (P?)	<i>Stenogobius psilosinionus</i>	?	?	
Brown gudgeon (C2)	<i>Eleotris fusca</i>	Adults 7 cm	?	

Common name (fish movement group)	Family, genus, species	Common length of fish	Flow condition/ migration timing	Fish movement capability
Ebony gudgeon (C2)	<i>Eleotris melanosoma</i>	Adults 7 cm	?	(average 0.12 m/s); prolonged speed limited to about 0.3 m/s • Purple spotted gudgeon: prefers low velocity habitats; capable of negotiating cascades and waterfalls
Empire gudgeon (C2)	<i>Hypseleotris compressa</i>	Adults 7 cm	Flood flow	
Fire tailed gudgeon (P3)	<i>Hypseleotris galii</i>	Adults 5 cm	Flood flow	
Midgley's carp gudgeon (P3)	<i>Hypseleotris sp. 1</i>	Adults 5 cm	Flood flow	
Poreless gudgeon (P3)	<i>Oxyeleotris nullipora</i>	Adults 3 cm	Flood flow	
Purple spotted gudgeon (P3)	<i>Mogurnda adspersa</i>	Adults 8 cm	?	
Purple spotted gudgeon (P3)	<i>Mogurnda adspersa</i>	Adults 8 cm	?	
Legend	TL = total length of fish	NV95 = maximum velocity of water that 95% of fish of one size class can negotiate – approximates burst swim speed for this experiment		

Note: The swimming ability data presented here was synthesised from various sources which are referenced in Kapitzke (2006).

Source: Kapitzke (2006).

B.2.2 EXTRACT FROM FISH MOVEMENT DATA FOR TULLY-MURRAY CATCHMENT

Table B.6: Fish movement direction for Tully-Murray fish species: Migration nature, movement direction, fish maturity and size, life-cycle stage, migration timing and flow – provisional

Common name	Family, genus, species	Life-cycle, spawning and migration (Fish movement group)	Upstream movement - obligatory			Downstream movement - obligatory			Localised movement (facultative) ALS/JLD/ALD/LFM	Comment
			Adult spawning AUS	Juvenile dispersal JUD	Adult dispersal AUD	Adult spawning ADS	Juvenile dispersal JDD	Adult dispersal ADD		
Biddies	Gerreidae									
Short finned silver biddy	<i>Gerres ovatus</i>	Amphidromous ?? – freshwater vagrant (M1)							?	Limited information on movement behaviour
Spotted silver biddy	<i>Gerres filamentosus</i>	Amphidromous – freshwater vagrant (M1)							LFM T / L	Juveniles commonly moving between marine and lowland freshwater reaches
Blue eyes	Pseudomugilidae									
Pacific blue-eye	<i>Pseudomugil signifer</i>	Potamodromous – local spawning, lowland to upland habitats (P3)							JLD/ALD	No known spawning migration; localised dispersal movement; no substantial broad scale dispersal migration
Spotted blue-eye	<i>Pseudomugil gertrudae</i>	Potamodromous – local spawning, lowland habitats (P4)							JLD/ALD	No known spawning migration; localised dispersal movement; no substantial broad scale dispersal migration
Cardinalfishes	Apogonidae									
Mouth almighty	<i>Glossamia aprion</i>	Potamodromous – local spawning, lowland to upland habitats (P3)		(✓)			(✓)		ALS L / H	Localised adult spawning migration to lagoons – low / high flows; apparent widespread dispersal movement

Common name	Family, genus, species	Life-cycle, spawning and migration (Fish movement group)	Upstream movement - obligatory			Downstream movement - obligatory			Localised movement (facultative) ALS/JLD/ALD/LFM	Comment
			Adult spawning AUS	Juvenile dispersal JUD	Adult dispersal AUD	Adult spawning ADS	Juvenile dispersal JDD	Adult dispersal ADD		
Eels	Anguillidae									
Long finned eel	<i>Anguilla reinhardtii</i>	Catadromous – marine to upland habitats (C1)		✓ _H	✓	✓ _H				Adult downstream spawning migration and juvenile upstream dispersal migration – high flows; adult upstream dispersal migration – unknown timing
Pacific short finned eel	<i>Anguilla obscura</i>	Catadromous – marine to upland habitats (C1)		✓	?	✓				Adult downstream spawning migration and juvenile upstream dispersal migration – unknown timing
Eel-tailed catfish	Plotosidae									
Black catfish	<i>Neosilurus ater</i>	Potamodromous – upland spawning (P1)	✓ _H				✓ _H	✓ _H		Highly synchronised adult upstream spawning migration, juvenile and adult downstream dispersal migration – high flow conditions

Source: Kapitzke (2006).

APPENDIX C VICTORIAN FISHWAY HYDRAULIC CRITERIA

Table C.1: Victorian fishway hydraulic performance criteria

Hydraulic Performance Criteria	Hydraulic Performance Standard
1. Minimum depth in fishway	<u>Vertical-slot fishways, fish locks:</u> 0.40 m minimum depth (0.5 m desirable) for small-bodied fish (20–100 mm) 0.75 m minimum depth (1.0 m desirable) for medium-bodied fish (100–650 mm) 1.0 m minimum depth (1.5 m desirable) for large-bodied fish (650–1400 mm). <u>Rock-ramp fishways:</u> Criteria presently being refined for rock-ramp fishways. Preliminary standards for the 'ridge design', which is a series of pools and ridges, include: - Minimum depth of 0.3 m for 50% of pool surface area, for small- to medium-bodied fish (20–150 mm) - Minimum depth of 0.5 m for 50% of pool surface area, for medium-bodied fish (150–400 mm) - Same minimum depths above and below 50% of gaps in ridge rocks - Same minimum depth providing a continuous path between ridges - Minimum depth of 0.15 m for 50% of ridge-rock gaps for small-bodied fish (20–100 mm) - Minimum depth of 0.3 m for 50% of ridge-rock gaps for medium-bodied fish (20–400 mm). Preliminary standards for the 'random-rock design', which is more like a roughened channel without discrete pools, include a minimum depth: - Of 0.3 m for a minimum 2 m of channel width for small-bodied fish (20–100 mm) - Of 0.4 m for a minimum 3 m of channel width for medium-bodied fish (100–400 mm) - Providing a continuous path of minimum depth from top to bottom of the ramp. Note: there are few data concerning minimum depth in rock fishways for large-bodied fish (>400 mm).
2. Maximum water velocity	Measured using head loss between baffles or pools and needs to be interpreted together with turbulence. <u>Vertical-slot fishways, fish lock entrance or exit. Head loss:</u> 0.075 ± 0.015 m for small-bodied fish (30–50 mm) 0.100 ± 0.020 m for small-bodied fish (40–100 mm) 0.165 ± 0.035 m for medium- and large-bodied fish. (100–1400 mm). <u>Rock-ramp fishways – ridge design</u> 0.075 ± 0.015 m for very small-bodied fish (15–40 mm) 0.100 ± 0.02 m for small-bodied fish (40–100 mm). <u>Connecting channels</u> Head loss is not applicable and direct measurement of velocity is used. <0.03 m/s for small-bodied fish >20 mm <0.10 m/s for medium-bodied fish >100 mm <0.30 m/s for medium-bodied fish >300 mm.
3. Turbulence	Not directly measured on site but calculated from head loss and pool volume (see Appendix 1): <u>Vertical-slot fishways</u> <30 Watts per cubic metre (W/m^3) (calculated using a Cd of 0.7) for small-bodied fish >25 mm <60 W/m^3 for medium-bodied fish >90 mm <90 W/m^3 for medium-bodied fish >150 mm. <u>Rock-ramp fishways (ridge-rock design)</u> <30 W/m^3 in pools. <u>Denil fishways</u> <10 W/m^3 in resting pools. <u>Fish locks</u> <20 W/m^3 in lock chamber.
4. Hydraulic gradient	<u>Denil fishways, rock-ramp fishways – random-rock design</u> Headwater depth entering fishway channel $\leq$ tailwater depth leaving fishway channel, within specified operating range of fishway.
5. Downstream passage	Regulator gates overshot, not undershot, as the latter causes mortality of larvae and juveniles. For weirs, plunge pool downstream of crest provides a depth that is >40% of the difference in upstream and downstream water level (i.e. head differential). For large dams, spilling water at the base of the dam has a gradual deceleration of 1.5 m s^{-2} per metre distance. No dissipators or structures on the downstream apron that could impact fish. (Note: these are recent criteria developed in the last 5 years, and many weirs may not comply).

Source: O'Connor, Mallen-Cooper & Stuart (2015)