



Mekong River Commission

Modelling the cumulative barrier and passage effects of mainstream hydropower dams on migratory fish populations in the Lower Mekong Basin

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Meeting the Needs, Keeping the Balance



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Editor: T.J. Burnhill

Graphic design: T.J. Burnhill

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184 Fa Ngoum Road, Unit 18, Ban Sithane Neua, Sikhottabong District,
Vientiane 01000, Lao PDR

Telephone: (856-21) 263 263 Facsimile: (856-21) 263 264

E-mail: mrcs@mrcmekong.org

Website: www.mrcmekong.org

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Glossary

AMCF: Assessment of Mekong Capture Fisheries

Anadromous species: Species which feed and grow mostly in marine environments but which reproduce in freshwater.

Blackfish: Species that possess morphological and physiological adaptations to extreme environmental conditions including low dissolved oxygen and desiccation. Typically floodplain resident species or inhabiting lentic (still water) environments.

Catadromous species: Species which feed and grow in freshwater but reproduce in marine environments.

Critical habitat: Habitat required by a species to complete its life-cycle.

Doubling time: The time taken to produce a doubling of population size.

Fecundity: The potential reproductive capacity of an organism or population. Fecundity often refers to the number of viable eggs produced by an individual or population.

FishBase: An information system on the world's fishes. The global data base is available on Internet at <http://www.fishbase.org/>.

Guild: A group of species that exploit the same class of environmental resources in a similar way. This term groups together species that overlap significantly in their niche requirements. In this analysis the term is defined primarily by spawning and breeding behaviour.

Intrinsic population growth rate: A value that quantifies how much a population can increase between successive time periods.

Iteroparous species: Species able to breed more than once during their lifetime.

Parameter: A measure of some aspect usually expressed as a numerical value, e.g., natural mortality rate or growth.

Persistence: The tendency of a population to continue to exist in the long term, despite short-term fluctuations.

Potamodromous species: Species inhabiting freshwater throughout their life cycle.

Potamon: The lowland depositional zone of a river, which is typically meandering and where much of the substrate is sand or silt and where the water is relatively deep, warm, and with low oxygen content.

Projection matrix model: A matrix giving the survival and fecundity of different length/age classes in a population. Used for projecting the population size between successive time periods.

Rithron: The upland erosional zone of a river, which is characterised by riffles and pools and where much of the substrate may be rocky and where the water is relatively shallow, cold and with high oxygen content.

Semelparous species: Species in which all sexually mature adults die after spawning. The salmonid genus *Oncorhynchus* exemplifies this pattern of behaviour (Wootton, 1990).

Viable population: A population having a good chance of surviving for a given number of years despite the foreseeable effects of demographic, environmental and genetic events, as well as natural catastrophes.

Whitefish: Migratory species intolerant to low dissolved oxygen concentrations and typically inhabit lotic (flowing water) environments. Species belonging to this category typically undertake longitudinal migrations in the main channel but may also undertake lateral migrations between the floodplain and main channel.

Glossary of functions and parameters (in order of appearance)

- F Annual instantaneous rate of mortality due to fishing.
- Pb Probability of turbine blade-strike.
- l Length of an individual fish.
- V_{axial} Axial water velocity at the turbine blades (a function of the geometry of the turbine and discharge rate).
- θ Angle of a fish relative to the turbine blade.
- n Number of blades present in the turbine.
- N Rotation rate of the turbine blades.
- MR The mutilation ratio. The ratio between the proportion of fish estimated to be struck by a turbine blade and the proportion observed to be injured.
- $M_{turbine}$ The probability of mortality from a turbine blade-strike event.
- $S_{turbine}$ Probability of surviving turbine passage.
- $\mathbf{n}_t$ The population vector at time t .
- n_j The number of individuals of length stage j .
- $\mathbf{A}_t$ The projection matrix at time t .
- $\mathbf{M}_t^{ab}$ Matrix specifying the probability of fish successfully migrating from habitat a to habitat b at time t .
- $\mathbf{A}^S, \mathbf{A}^F$, and $\mathbf{A}^R$ Sub-matrices describing demographic processes (growth, survival and reproduction) in the spawning (S), feeding (F) and refuge (R) habitat, respectively.
- $\mathbf{I}$ The unit matrix. An n -by- n square matrix with ones on the main diagonal and zeros elsewhere.
- P_j The probability of surviving and staying in length class j .

G_j	The probability of surviving and growing into the next length class j .
f_j	The average fecundity per fish for length-class j .
m_j^{ab}	The probability that an individual of length class j migrates from habitat a to habitat b at time t .
α	Upstream passage efficiency of fish pass i.e. the proportion of upstream migrating individuals that successfully pass the dam.
P_{RS}	The proportion of adults that enter the spawning habitat from the refuge habitat.
P_{RF}	The proportion of adults that enter the feeding habitat from the refuge habitat.
D	Number of dams included in the model.
P_{SF}	The proportion of individuals that successfully enter the feeding habitat from the spawning habitat during the downstream migration.
G_j	The probability of surviving and growing to the next length stage.
γ_j	The probability of an individual fish growing to the next length class j .
σ_j	The probability of individual fish surviving to the next length class j .
T_j	The average duration that an individual will remain in length class j , here approximated on the basis of a growth model.
P_j	The probability of an individual fish surviving, but not growing to the next length class.
Z_j	The total rate of is mortality at length stage j .
M_j	The instantaneous rate of natural mortality at length stage j .
l_m	Length at maturity, typically defined as the length at which 50 % of individuals in the population become sexually mature.
L_∞	The asymptotic length towards fish grow according to the von Bertalanffy growth function (VBGF).
M_W	The instantaneous rate of natural mortality at weight W .
M_u	The instantaneous rate of natural mortality at unit weight.

c	The allometric scaling factor of the mortality-weight model described by Lorenzen (1996).
L	Total length of an individual fish
W	Weight of an individual fish
a	Coefficient of the length-weight relationship
b	Exponent of the length-weight relationship
M_L	The instantaneous rate of natural mortality at length, L
K	Growth rate parameter of the VBGF.
L_{max}	Reported maximum total length of an individual fish
t_l	Age of fish at length l .
t_d	Population doubling time i.e. the time taken for a population to double in size.
r	Intrinsic population growth rate. The instantaneous rate of change of population size. Used in the exponential form of population growth models for populations with continuous reproductive events.
λ	Population growth rate. A finite measure of the rate of change in size of the population during a fixed time, typically a year. Used for geometric form of population growth models for populations with discrete (e.g. annual) reproductive events. Note: $\lambda = e^r$ or $\ln \lambda = r$.

Summary

Background

Many reviews have highlighted the exceptional importance, by global standards, of fish resources in the Lower Mekong Basin. Compared to many other river basins, the lower Mekong currently remains relatively undeveloped from a hydropower perspective. However, during the last two years, renewed interest in mainstream hydropower projects has emerged. There are now proposals for 11 dams to be located on the mainstream between northern Lao PDR and northern Cambodia. Globally, the construction of dams for hydropower, irrigation and navigation has been a major cause of change to freshwater ecosystems altering flows, interrupting ecological connectivity of river systems and fragmenting habitats. The impacts of dams on river fisheries resources are varied, often profound and typically mediated through two major pathways: (i) flow modification, and (ii) barrier and passage effects.

Flow modifications impact upon fish populations and fish communities by disrupting and diminishing spawning behaviour and success, and by reducing growth and survival rates arising from diminished feeding and refuge opportunities and exposure to unfavourable environmental conditions.

Barrier and passage effects on fish populations may be particularly significant and are the subject of this study. Dams can deny or diminish fish access to critical or upstream spawning habitat but also have the potential to reduce population survival rates as adult fish and their progeny returning to downstream feeding and refuge habitat pass through dam turbines, by-pass structures, or over dam spillways. The combination of diminished survival rates and spawning success can lead to significant reductions in exploitable fish biomass and species extinctions.

With the support of the Mekong River Commission (MRC), the riparian governments of the LMB are pursuing an integrated water resource management (IWRM) approach to plan and coordinate the sustainable, equitable, efficient and pro-poor development of the water and related resources of the LMB. Exploring the potential for hydropower development whilst also conserving and sustaining the fisheries resources of the basin is central to the MRC Secretariat's Basin Development Plan (BDP) and the IWRM process. This study seeks to contribute to these planning processes by developing and applying a model to examine the likely impact of the proposed mainstream hydropower dams on the basin's fisheries resources caused by their potential barrier and passage effects on highly migratory fish populations. Flow change impacts are currently being explored in a related project within the MRC Fisheries Programme.

Identifying species at risk

Not all species of fish caught in the basin are threatened by mainstream dams. Some species have only limited migrations over short ranges which may not be impaired by dam structures whilst others are highly adaptable to habitat modification including impoundment. Species of

fish most likely to be impacted will be those that undertake significant (passive and active) migrations between critical (spawning, feeding, and refuge) habitat to complete their life-cycles or to exploit seasonal variation in habitat quality and availability.

Using an environmental guild framework and data collected under catch monitoring programmes, we identified 58 highly migratory species threatened by mainstream dam development. They include 5 of the 11 Mekong fish species threatened by extinction according to the IUCN 'Red List': the Mekong giant catfish (*Pangasianodon gigas*), the Mekong stingray (*Dasyatis laosensis*), Jullien's barb (*Probarbus jullieni*), the Laotian shad (*Tenualosa thibaudeaui*) and the Thicklip barb (*Probarbus labeamajor*). These 58 vulnerable species contributed to 38.5% of the total weight of all 233 species recorded in catch surveys with an estimated value in the basin in excess of US\$1,000 million per annum.

Twelve species representing different families, migratory behaviour and life history strategies were selected for detailed modelling. Two species (the small scale tongue-sole, *Cynoglossus microlepis* and the giant river prawn, *Macrobrachium rosenbergii*) were later dropped from the study because reliable model parameter estimates could not be made for these species.

Modelling upstream and downstream migration impacts

Using the best available knowledge and data we developed a length-based projection matrix model to describe the dynamics of simulated populations of the remaining 10 model species in response to variable passage success rates to upstream spawning habitat via fish ladders or other fish passes, and elevated downstream natural mortality rates on adults and juveniles returning to downstream feeding and refuge habitat via dam turbines, spillways or by-passes. These responses were modelled for fish populations obliged to pass up to three dams to complete their life cycles. Whilst proposals for up to 11 mainstream dams exist, the inclusion of a maximum of three dams in the model generated sufficient information to illustrate the cumulative barrier and passage effects of multiple mainstream dams on these migratory fish populations and to reveal the necessary range of minimum mitigation targets to maintain viable populations. The model can, however, include any number of dams. The model builds upon published research and model development for dam impact prediction and assessment purposes particularly for systems in North America (Columbia River basin) and Sweden.

Downstream mortality was described using a blade-strike model developed for Kaplan type turbines that feature in most of the proposed mainstream dams in the LMB. In the model simulations, the proportion of adults returning through the turbines was varied from 25% to 100%. Based upon their limited capacity to avoid entrainment and the ability of engineers to effectively screen turbines from small individuals without compromising turbine efficiency, all juveniles returning from upstream spawning habitat were assumed to pass through the dam turbines. However, the model was found to be insensitive to this assumption because returning juveniles are typically small and therefore experience low turbine mortality. Other important assumptions underlying the study are summarized in the table below.

The main assumptions underlying the modelling study.

Subject	Assumptions	Comments and Recommendations
Proportion of catch in the LMB identified as vulnerable.	MRC catch assessment survey (CAS) provides a representative sample of total landings by species in the LMB.	- Unlikely to be valid given that the CAS mostly targeted gillnet fishers operating in the mainstream but no better alternatives. - More reliable estimates would require a basin-wide and species-wise household or fisher-based catch assessment survey with appropriate stratification to account for temporal, spatial and habitat-dependent variation in fish catches.
Longitudinal distribution of critical habitat.	- All spawning habitat is located upstream (above) of the uppermost dam, and - All feeding and nursery habitat is located downstream of (below) the lowermost dam.	- Sensitivity of results to these assumption not examined, but likely to be high. - Undertake a sensitivity analysis for a range of alternative assumptions concerning spawning habitat distribution (e.g. normal, uniform, skewed...etc) and/or incorporate empirical model of distribution based upon larvae surveys.
Population structure.	Species assumed to comprise a single population in the LMB.	- Sensitivity of results to this assumption not examined, but likely to be high. - More DNA studies required.
Upstream passage of adults to spawning grounds.	No mortality or diminished reproductive capacity associated with upstream passage via ladders or other passes.	Some mortality and diminished reproductive capacity expected due to high energetic costs associated with passage and increased likelihood of predation in dam vicinity. Results therefore likely to be conservative.
Downstream passage of juveniles.	All juvenile fish pass downstream through dam turbines.	Juvenile fish have limited capacity to avoid entrainment (swimming capacity is a function of fish length). Limited ability to screen turbines without compromising turbine efficiency. Results insensitive to this assumption.
Downstream passage of adults and juveniles via spillways or by-passes	Mortality rates are zero for these passage routes.	Some mortality is likely so results may be conservative.
Downstream passage of adults and juveniles via turbines.	Mortality rates can be accurately predicted by the turbine geometry and rotation speed selected.	Mortality rates of medium size fish may be overestimated if turbine rotation speeds are lower than those selected but this is unlikely to affect the study conclusions given the other assumptions concerning fish passage. Re-run model when actual turbine rotation speeds and geometry are known.

Results

Species size described by its maximum length was found to be an important factor determining the magnitude of dam impacts. We therefore structure the results by small (< 50 cm) and large species (>50 cm).

Downstream mortality

Adults of the small species: *H. siamensis*, *H. lobatus*, *G. pennockii*, *P. typus* and *B. helodes* are predicted to experience relatively low mortality rates during their return migrations from upstream spawning habitat ranging from approximately 2%–15% per dam crossed assuming all individuals pass through the turbines. This declines to less than 5% under the assumption that 75% of individuals could be safely by-passed via spillways, by-pass channels or sediment sluices.

Spawning adults of the large species on the other hand experience very high rates of mortality if they pass through turbines ranging from approximately 35% for *H. malcolmi* and 70% for *C. harmandii* to 100% probability of mortality for *P. gigas*, *P. jullieni* and 80% for *P. conchophilus*.

Minimum upstream passage success to sustain wild populations

Upstream passage success rate was defined as the proportion of the fish that succeed when attempting to pass the dam. Minimum upstream passage success rates to maintain viable populations of each species were determined, where viable populations were defined as those with intrinsic population growth rates (λ) values greater than or equal to one (i.e. growing or static population size) under combinations of the following assumptions or conditions:

- One, two, or three dams;
- Exploitation or no exploitation. For the exploited condition, annual instantaneous rates of fishing mortality, F were set at 0.5 y⁻¹ for the small species and 0.1 y⁻¹ for large species based upon the available estimates in the literature;
- High, medium and low reproductive potential estimated from population doubling times quoted in FishBase.
- Proportion (%) of downstream migrating adults directed passed (avoiding) dam turbines.

Populations will decline in size if their intrinsic population growth rate (λ) falls below a value of 1.

Small species

Faced with the downstream survival rates described above, the model predicted that to maintain viable exploited populations of the small species included in the model, fish ladders, locks or other structures would need to pass at least 60% to 87% of upstream migrating adults in the case of a single dam, rising to 80% to 95% if adult fish were obliged to cross two or more dams, to reach critical upstream spawning habitat (table below). For these small species, minimum upstream passage success was found to be relatively insensitive to the proportion of adults passing downstream via the turbines. Attempts to reduce these minimum upstream passage success thresholds by improving downstream passage survival are predicted to be ineffective for small species (table below).

Predicted minimum upstream passage success rate (%) to maintain viable populations of the five small species of fish included in the model under different assumptions and conditions. For brevity only results for the most conservative high reproductive potential assumption are shown.

Species	% of adults via turbine	1 Dam		2 Dams		3 Dams	
		NE	E	NE	E	NE	E
<i>H. lobatus</i> (Lesser silver mud carp)	25	53	86	73	93	81	95
	50	53	86	73	93	81	95
	100	53	87	73	94	82	96
<i>H. siamensis</i> (Siamese mud carp)	25	44	72	67	85	77	90
	50	44	72	67	85	77	90
	100	45	73	68	86	77	91
<i>P. typus</i> (Pelagic river carp)	25	45	70	67	84	77	89
	50	45	71	68	84	77	89
	100	45	71	68	85	78	90
<i>G. pennocki</i> (Spotted algae eater)	25	34	60	59	78	71	85
	50	34	60	60	79	72	86
	100	35	61	62	80	74	88
<i>B. helodes</i> (Tiger botia)	25	39	72	64	86	75	91
	50	40	73	66	87	77	93
	100	42	75	69	90	81	95

Note: E—with exploitation (fishing); NE—No exploitation (no fishing).

Large Species

Large species appear particularly vulnerable to the downstream passage effects of dams. These are predicted to be terminal for exploited populations of *P. jullieni* and *P. gigas* even if engineering solutions could be developed to re-direct 75% of downstream migrating adults away from dam turbines and if upstream migrations were completely unhindered i.e. 100% upstream passage success. The model predicts that maintaining viable populations of *P. gigas* would require a complete ban on fishing for this species and near perfect engineering solutions i.e. 0% of adults passing through turbines and 90% to 100% upstream passage efficiency.

Predicted minimum upstream passage success rates (%) to maintain viable populations of the five large species of fish included in the model under different assumptions and conditions. For brevity only results for the most conservative high reproductive potential assumption are shown.

Species	% of adults via turbine	1 Dam		2 Dams		3 Dams	
		NE	E	NE	E	NE	E
<i>H. malcolmi</i> (Goldfin tinfoil barb)	25	63	80	x	x	x	x
	50	72	91	x	x	x	x
	100	99	x	x	x	x	x
<i>C. harmandii</i> (Green giant barb)	25	60	85	x	x	x	x
	50	97	x	x	x	x	x
	100	x	x	x	x	x	x
<i>P. concophilus</i> (Sharp-nosed catfish)	25	65	90	x	x	x	x
	50	x	x	x	x	x	x
	100	x	x	x	x	x	x
<i>P. jullieni</i> (Jullien's barb)	25	x	x	x	x	x	x
	50	x	x	x	x	x	x
	100	x	x	x	x	x	x
<i>P. gigas</i> (Mekong giant catfish)	25	x	x	x	x	x	x
	50	x	x	x	x	x	x
	100	x	x	x	x	x	x

Note: E—with exploitation (fishing); NE—No exploitation (no fishing). x—indicates combinations give rise to populations that are not viable.

In the case of a single dam, the model predicts that exploited populations of the remaining large species would remain viable only if upstream passage success exceeded 80% and if 75% of returning adults could be re-directed away from turbines. Only *P. concophilus* is predicted to persist in the case of two dams if upstream passage success exceeded 90% and if 75% of returning adults could be re-directed away from turbines. No large species are predicted to persist if three dams have to be crossed or if their reproductive potential is low. With potentially increasing rates of exploitation from a growing basin population and the prospect of multiple dam obstructions, fears surrounding the persistence of *P. gigas* (and other large species) appear warranted.

Mainstream dams in the LMB have the potential to diminish fish diversity and the size structure of the community thereby potentially impacting upon ecosystem integrity and functioning. Overall catch value may also decline if large, valuable, highly migratory species no longer persist at levels that are economically attractive to fishers. Populations of small species that respond rapidly to, or 'track', environmental variation may also decline further, diminishing their resilience to climate change and leading to greater inter-annual variability in landings.

Mitigation

Because downstream survival rates of fish are modelled as length-dependent, the model predicts that populations of larger species are more likely to respond to efforts to re-direct downstream

migrating adults away from turbines. For smaller species, redirecting fish away from a turbine appears to have little impact on the required minimum up-stream passage success rate.

Mitigation strategies aimed at improving the downstream survival of juveniles of any species are also likely to generate marginal benefits often only after very high research, development and investment cost. The model suggests that attempts to improve downstream survival should focus upon the adults of large species.

Estimates of downstream passage success (survival) reported in the literature range from 0% to 100%, with average upper and lower estimates ranging from approximately 40% to 70%, several of which refer to juvenile stages only.

We were unable to find evidence in the literature to suggest that the necessary rates of upstream passage success to sustain even the small species summarized above have been achieved elsewhere.

Only after some 30 years of research and development at a cost of more than US\$7,000 million, attempts to mitigate dam impacts on Pacific salmon populations in the Columbia River basin have been relatively successful compared to those in tropical systems. Besides their strong swimming capacity to negotiate ladders or bypasses, an important reason for this success may be lie in the semelparous reproductive behaviour of this species. Adult Pacific salmon die shortly after spawning and therefore are not subject to the strong size-dependent downstream passage mortality effects predicted here. In river systems such as the Mekong, adults of medium and large size iteroparous species (species that reproduce more than once during their lifetime) may need to undertake several spawning migrations in their life-time to maintain viable populations. It is these large adult fish that experience significant rates of mortality during their downstream passage through dams.

Whether considering either downstream survival or upstream passage, the diversity of fish species inhabiting the tropical systems including the Mekong is also likely to raise significant challenges to designing engineering solutions for species or groups of species sharing similar behaviour and swimming capacity often determined by body size.

The hypothesis that dams built in the upper reaches of rivers have less impact than those built in downstream locations assumes: (i) the distribution of spawning habitat is either uniform throughout the range of the species, skewed towards the downstream reaches, or absent from upstream reaches and/or (ii) one or more discrete populations of the species exist in the system, distributed longitudinally.

We believe data and information concerning both the distribution of spawning habitat in the basin and the population structure are currently inadequate to determine if these assumptions are reasonable for most of the species examined here. All dams, regardless of their location should be regarded as a significant threat to the viability of fish population in the Mekong, particularly those of large species. Furthermore, fewer options to mitigate the barrier effects of dams may exist in the upper reaches of the basin particularly where the channel is flanked by

hills or mountains and the channel gradient is steep requiring greater dam heights. Options for mitigation in the LMB are examined in detail by Baran *et al* (2009).

Future work to improve the model

We believe this is the first attempt to construct a model that explicitly accounts for size-(age) dependent migrations between critical habitat via multiple dam structures on the dynamics and sustainability of highly migratory iteroparous fish species.

Because we are unable to validate the model by comparing its predictions against observations, the accuracy of the model predictions cannot be determined except that the model does appear to effectively simulate inter-annual changes in the size structure of fish populations monitored under catch assessment surveys. The model should therefore be regarded as a tool to explore likely response of highly migratory fish stocks to the barrier and passage effects of multiple mainstream dam structures and help identify strategies to mitigate these effects.

Whilst our model predictions were not subject to a systematic sensitivity analysis by applying incremental changes to each base parameter estimate in turn, the study did explore a large ‘parameter space’ by including a wide range of fish life history strategies in the model and by testing the possible range of passage efficiency both upstream and downstream. We also explored the sensitivity of the model predictions to uncertainty surrounding the estimated population growth rate and the presence and absence of harvesting.

To reduce uncertainty in our model predictions we propose a second phase of model development. We recommend this include simulations under different assumptions concerning the distribution of critical habitats (e.g. normal, uniform, skewed... etc) in relation to the proposed dam locations and the inclusion of stochastic population growth to mimic the effects of inter-annual variation in flow or other climate-dependent variables on growth, survival and reproductive success.

A catadromous life cycle (characterized by feeding and growth in freshwater with reproduction at sea) should also be included in future models to determine if populations of species belonging to this migratory behaviour category respond in the same manner to barrier and passage effects as the potadromous species (migrations occurring entirely in freshwater) examined here.

Few estimates of fishing mortality (F) exist for species exploited in the LMB. The analysis of length-frequency data generated by a well-designed, short duration basin-wide survey could provide more reliable estimates of fishing mortality for the model species. Estimates of fish fecundity at length could also be derived on the basis of similar short-term biological surveys. Further research is also required to determine the population structure of threatened species. Mitochondrial DNA analyses of the type described by Hurwood *et al* (2006) appear promising requiring little time and few resources.

Any future model development should also aim to reduce uncertainty in the model predictions by revising the existing blade-strike downstream passage mortality model with turbine rotation speeds more typical of the actual proposed projects once they have been finalised by the developers and engineers.

The table below summarises the sources of uncertainty surrounding the model predictions, and recommended action to reduce or report this uncertainty. Uncertainty surrounding the model predictions arises from a combination of process, observation or measurement, and model uncertainty. The table also indicates the relative importance of these sources to the overall study conclusions, recommended action, and relative required time and resources.

Sources of uncertainty surrounding model predictions and recommended action.

Sources of uncertainty	Description and (importance)	Action, comments and (required resources)
Model Uncertainty (mis-specification of the model structure)	Distribution of spawning habitat relative to dam locations (**).	To report uncertainty repeat simulations with different assumptions concerning the distribution of spawning habitat. May require some re-structuring of the existing model (++).
		To reduce uncertainty repeat simulations incorporating spawning habitat distribution based upon results of 'Ichthyoplankton Survey'. May require some re-structuring of the existing model (+++).
	Catadromous life cycles (*).	To reduce uncertainty repeat simulations using catadromous life-cycle model for catadromous species. Catadromous species relatively unimportant in terms of landings in the LMB. May require some re-structuring of the existing model (++).
	Population structure (**)	To report uncertainty repeat simulations with different assumptions concerning the population structure of each species. Will require re-structuring of the existing model (+++).
		To reduce uncertainty repeat simulations with appropriate population structures for each species based upon DNA studies. Will require a basin-wide tissue sampling programme and re-structuring of the existing model (+++).
Process Uncertainty (random variability in population dynamics)	Environmental effects (*).	To report uncertainty arising from environmental variation repeat simulations incorporating vital population growth rates as a function of the environmental variables such as flow levels, oxygen concentration and water temperature (++).
Observation or Measurement Uncertainty (arises from the collection or measurement of variables)	Estimates of turbine blade strike mortality (**).	To reduce uncertainty repeat simulations incorporating turbine rotation speeds for Mekong projects provided by project developers (+). But note that other sources of downstream mortality are not included.
	Fishing mortality, F (*).	To reduce uncertainty repeat simulations incorporating estimates of F for the model species derived from length-frequency samples across the basin (++).
	Fecundity estimates (*)	To reduce uncertainty repeat simulations incorporating estimates of fecundity at length for the model species (++).

Note: Relative importance of sources of uncertainty for study conclusions: * low; ** medium; *** high. Required time and resources: + low; ++ medium; +++ high.

1. Introduction

1.1 Study context and purpose

Fisheries resources in the Lower Mekong Basin

Many reviews have highlighted the exceptional importance, by global standards, of fish resources in the Lower Mekong Basin (e.g. Lagler, 1976; Jensen, 2000; Van Zalinge *et al.*, 2004; Baran *et al.*, 2007; Hortle, 2007). Based upon the results of fish consumption surveys, total annual landings of fish (excluding aquaculture) from the LMB have been estimated to be in the order of 1.9 million tonnes with a first sale of value in excess of US\$2 billion (Barlow *et al.*, 2008). This is in addition to the economic benefits that flow from the trade and processing of fish products and the very considerable indirect values of the fisheries resources, such as their contribution to the nutrition, employment and well-being of millions of rural people in the LMB, who generally have few alternative livelihood options. The LMB supports diverse fish fauna comprising at least 1,000 species, many of which are endemic including the endangered Mekong giant catfish *Pangasianodon gigas* (see Baran *et al.*, 2007, Hortle, 2007, and Poulsen *et al.* 2004 for reviews).

Hydropower Development

During the last century, dams have become a significant tool for the management and exploitation of water resources. More than 45,000 dams now exist globally with a height in excess of 15 m (Scruton *et al.*, 2008; Williams, 2008). Recent estimates indicate that dams service as much as 40% or irrigated land worldwide and that dams generate 19% of world electricity (WCD,2000).

Table 1.1 *Hydropower dams on the mainstream of the Mekong and tributaries.*

	Mainstream		Tributaries		Total
	Existing or under construction	Planned	Existing or under construction	Planned	
China	5	3	0	0	8
Lao PDR	0	6	14	19	39
Lao PDR/Thailand	0	2	6	0	8
Cambodia	0	2	0	4	6
Viet Nam	0	0	10	2	12
Total	5	13	30	25	73

Compared to other river basins such as the Columbia in North America, the lower Mekong remains relatively undeveloped from hydropower perspective. Currently there are 30 hydropower dams in operation or under construction in the tributaries of the lower Mekong but only 3 on the mainstream—all in the upper basin in Yunnan Province, China (Table 1.1 and Figure 1.1).

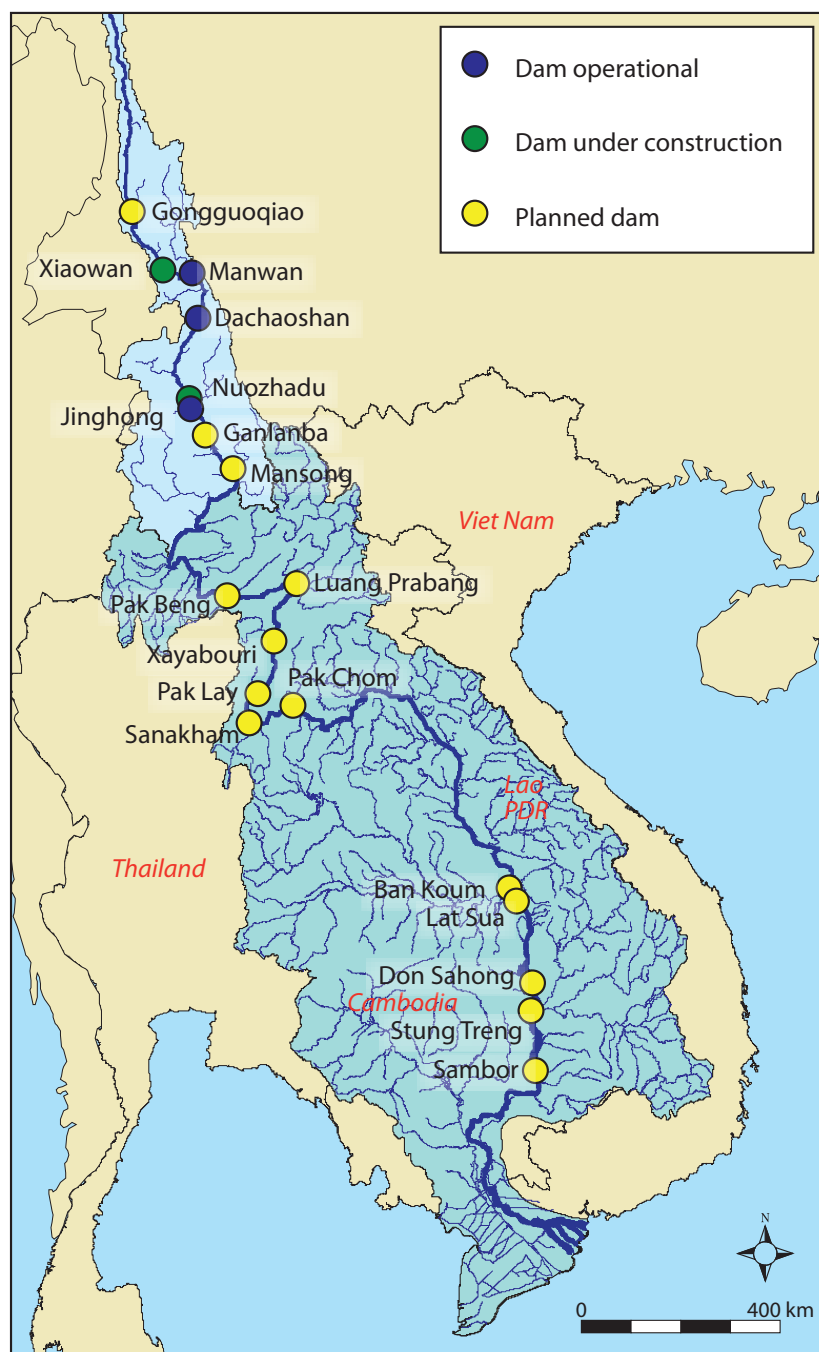


Figure 1.1 The locations of the 11 proposed hydropower dams on the Mekong mainstream in the Lower Mekong Basin that will be modelled and assessed as part of the MRC's Basin Development Plan. Also shown are mainstream dams in existence, under construction and proposed in the Upper Mekong (Lancang River) Basin.

Preliminary designs have been developed for 11 sites (Figure 1.1). Some, including Stung Treng and Sambor, have design origins dating back to the late 1960s. Each proposal shares a similar design concept to create a low step in the river where electricity could be generated, having a gated spillway, one or two power houses and a navigation lock arranged in line across the river. Estimates of installed capacity vary between 360 MW to 3,300 MW. Dam heights vary from 22 m to 68 m creating upstream inundated areas of between 2 km² and 800 km² (Table 1.2). Project layout figures illustrating the main design features of each proposal including its position in the channel were provided together with illustrations of the cross sections of power houses, sediment sluices and spillways. The positions of up to two fish ladders are also included in the illustrations. Although no accompanying details are provided, the report states that designs include, ‘...appropriate facilities to assist in the [upstream] passage of fish past the barrage... and may comprise...fish ladders, fish lifts or locks, and water flow arrangements to attract fish to the conveyance devices...[but that] ...suitable designs cannot be suggested at this time’ No mention is made of downstream fish passage facilities, but the report states that, ‘Fish will pass downstream through the projects with little difficulty at all seasons’ (Mekong Secretariat, 1994a).

Table 1.2 *Summary of key features of the 11 proposed mainstream hydropower dams in the LMB.*

Project name	Installed capacity (MW)	Dam height (m)	Live Storage (106 m ³)	Inundated area (km ²)	Approx. max. head at spillway (m)	Turbine type (number)
Pak Beng	1230	62	442	110	31	Kaplan (10)
Luang Prabang	1410	68	734	110	40	Kaplan (10)
Xayabouri	1260	53	224	30	24	Kaplan (10)
Pak Lay	1320	54	385	110	26	Kaplan (10)
Sanakham	1200	38	106		25	Kaplan (6)
Pak Chom	1079	55	12		22	
Ban Koum	1872	53	0	158	19	Kaplan (20)
Lat Sua	800	NA	0		10	
Don Sahong	360	10.6	115	1.6	-	Bulb (4)
Stung Treng	980	22	70		15	Kaplan (16)
Sambor	3300	35	2000	880	33	Kaplan (26)

Notes: Blank cells—no data available. Data Source: BDP2 Hydropower Project Database (2009); and Mekong Secretariat (1994a) for Inundated area and turbine related data. The approximate maximum head at the spillway is assumed to be equal to the ‘Rated Head’ quoted in the Hydropower Project Database.

Importantly for the model development purposes and related assumptions described in Chapter 2.3 no information is provided describing the proportions of the total river flow that will pass through the main flow structures (turbines; spillway and any fish by-passes) of each barrage. These flow proportions are important for predicting the likely route that downstream migrating fish are likely to follow as they attempt to pass through each barrage (Zabel *et al.*, 2008). Assumptions about these flow proportions are described further in Chapter 2.3.

The social impact of each proposal was judged solely in terms of the numbers of people who would be displaced. Various economic performance indicators were also used to identify the most attractive options but the report notes that, ‘Socioeconomic and environmental questions

remain to be closely looked into...'. Based upon these criteria, Don Sahong along with Ban Koum, Sayaburi and Pak Beng were identified as the most attractive options and classified as 'First Category Projects'.

The report conceded that there was a paucity of data and information concerning, '... important fish stocks and migration patterns, locations and characteristics of spawning and rearing habitats; and [therefore] that projects cannot be safely designed or mitigated without first establishing a sound and reliable database'.

Since 2007, the riparian governments of the LMB have expressed renewed interest in these 11 mainstream dam proposals presumably driven by rising energy costs. To date, Memoranda of Understanding (MOU) for feasibility studies have been signed between investors and the riparian governments of Lao PDR and Thailand for 8 of the 11 proposals (MRC, pers comms).

Threats to fisheries resources and dependent livelihoods

Globally, the construction of dams for hydropower, irrigation and navigation has been a major cause of change to freshwater ecosystems altering flows, interrupting ecological connectivity of river systems and fragmenting habitats. An estimated 40–80 million people have been displaced by dams and 60% of the world's rivers have been affected by dams (WCD,2000).

Large dams typically have third-order impacts on ecosystems (and dependent livelihoods) involving alterations to (fish) fauna (WCD, 2000). The impacts on river fisheries resources are varied, often profound and typically mediated through two major pathways: (i) flow modification, and (ii) barrier and passage effects (Figure 1.2).

Barrier and passage effects on fish populations are particularly significant and form the primary focus of this study. Dams can deny or diminish fish access to critical¹ or upstream spawning habitat but also have the potential to reduce population survival rates as adult fish and their progeny incur mortality passing through dam turbines, by-pass structures, or over dam spillways when returning to downstream feeding and refuge habitat. The combination of diminished survival rates and spawning success can lead to significant reductions in exploitable fish biomass and species extinctions as reported in river basins throughout the world (see WCD, 2000, Welcomme, 1985; Welcomme and Halls, 2001, and Halls, 1998, for reviews).

Whilst not the primary focus of this study, flow changes impact upon fish populations and fish communities by disrupting and diminishing spawning behaviour and success, and by reducing growth and survival rates arising from diminished feeding and refuge opportunities and exposure to unfavourable environmental conditions (ibid.).

The MRC's Basin Development Programme (BDP) is exploring the probable magnitude of hydrological changes arising from proposed development within both the lower and upper

¹ Critical habitats are areas crucial to the survival of particular species, populations and ecological communities.

Mekong basins. The preliminary results of these investigations indicate that future changes to the hydrology of the system will be most significant in the northern part of the LMB caused by large storages of water (approx. 33 km³) behind the Chinese dams, particularly Xiowan and Nuozhadu (Figure 1.1). For example, in Luang Prabang, Lao PDR, wet season flows under the ‘LMB 20 Year Scenario’ are predicted to decline by about 13%, while dry season flows will increase by an estimated 38%. Flooding will also be delayed (and shortened) by approximately two weeks. In Kratie, north-west Cambodia, the wet season flow is forecasted to decline by approximately 7% and the dry season flow is likely to increase by approximately 12%. Flooding will be delayed (and shortened) by approximately two weeks (MRC Internal Technical Note dated March 18 2009).

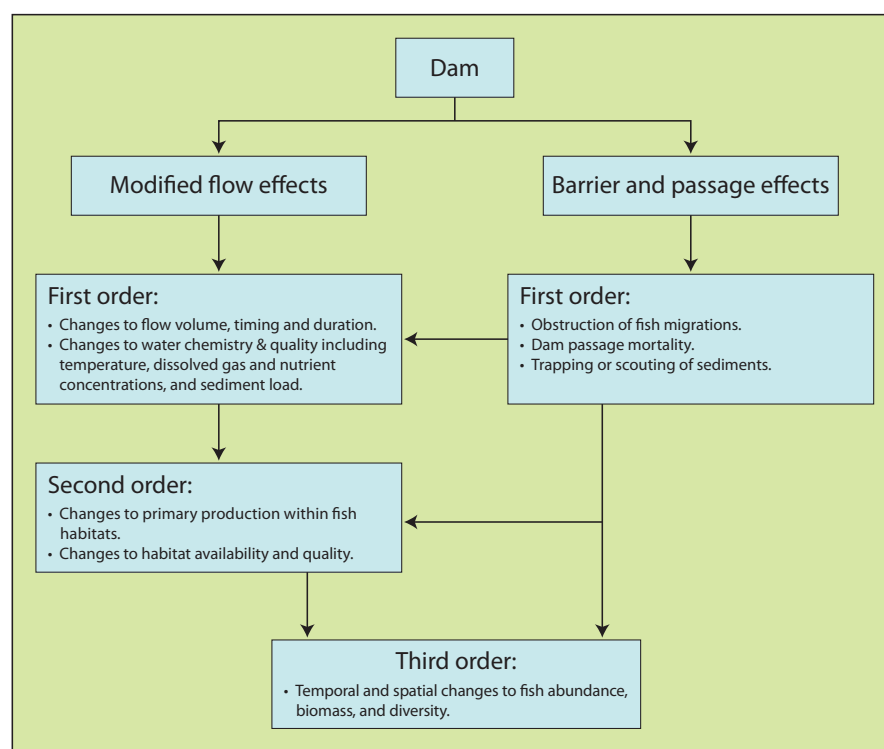


Figure 1.2 Dam impact pathways on fisheries resources.

The volume of water in Tonle Sap–Great Lake (TS–GL) system may decline by as much as 11% on average in wet season but is likely to increase by 7% on average in dry season (MRC Internal Technical Note dated March 18 2009). The net effect is that the aquatic terrestrial transition zone (ATTZ) or flood margin (Junk *et al.* 1989) may shrink by more than 11% on average. The size of this zone is believed to be a significant factor affecting nutrient recycling and thereby fish production. ‘Significant hydrological changes...’ are also expected in some tributary basins. (BDP presentation at the Regional Multi-stakeholder Consultation on the MRC’s Hydropower Programme, 25–27, September, 2008).

The likely impact of these changes to flow conditions in the basin and their effect on fish production is currently being explored by the MRC's Fisheries Programme. This includes the development of empirical multi-species models to predict how exploitable fish biomass is likely to respond to the modification of the basin's hydrological regime (see Halls *et al.*, 2008, for further details).

The proposed developments will cause changes in water quality and sediment transport, which are being investigated by the BDP.

Project Purpose

The purpose of this project is to develop a population dynamics model capable of making quantitative predictions of the cumulative impact of the barrier effects of mainstream hydropower dams on highly migratory fish populations inhabiting the Lower Mekong Basin (LMB). Such information is needed to contribute to the socioeconomic assessments of hydropower development on the mainstream of the Mekong currently being undertaken by MRC in conjunction with national planning agencies.

1.2 Study approach and report structure

Not all species of fish caught in the basin will be threatened by mainstream dams. Some species have only limited migrations over short ranges which may not be impaired by dam structures whilst others are highly adaptable to habitat modification including impoundment. Species of fish most likely to be impacted will be those that undertake significant (passive and active) migrations between critical (spawning, feeding, and refuge) habitat to complete their life-cycles or to exploit seasonal variation in habitat quality and availability. Therefore an important first task was to attempt to identify which species are likely to be most vulnerable. Data and information concerning the distribution of their critical habitat and their migrations between critical habitat type was then assembled to develop and parameterize a spatially-structured population matrix model (Quinn & Deriso, 1999). The model was then applied to determine the likely impact of the dams on the fish populations judged in terms of the minimum upstream passage efficiency (proportion of the adult population that successfully passes upstream through dam fish passage structures) of each dam to maintain viable fish populations defined as populations with stable or growing numbers of individuals. Model sensitivity analysis was then undertaken to test the robustness of the model to the underlying assumptions and to guide the identification of areas of the model that require further investigation or development (Figure 1.3).

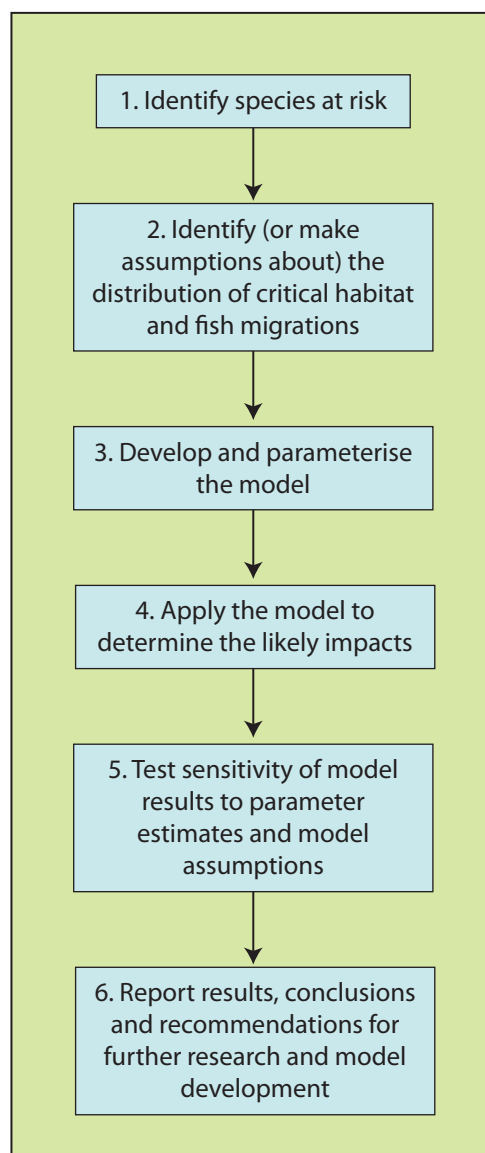
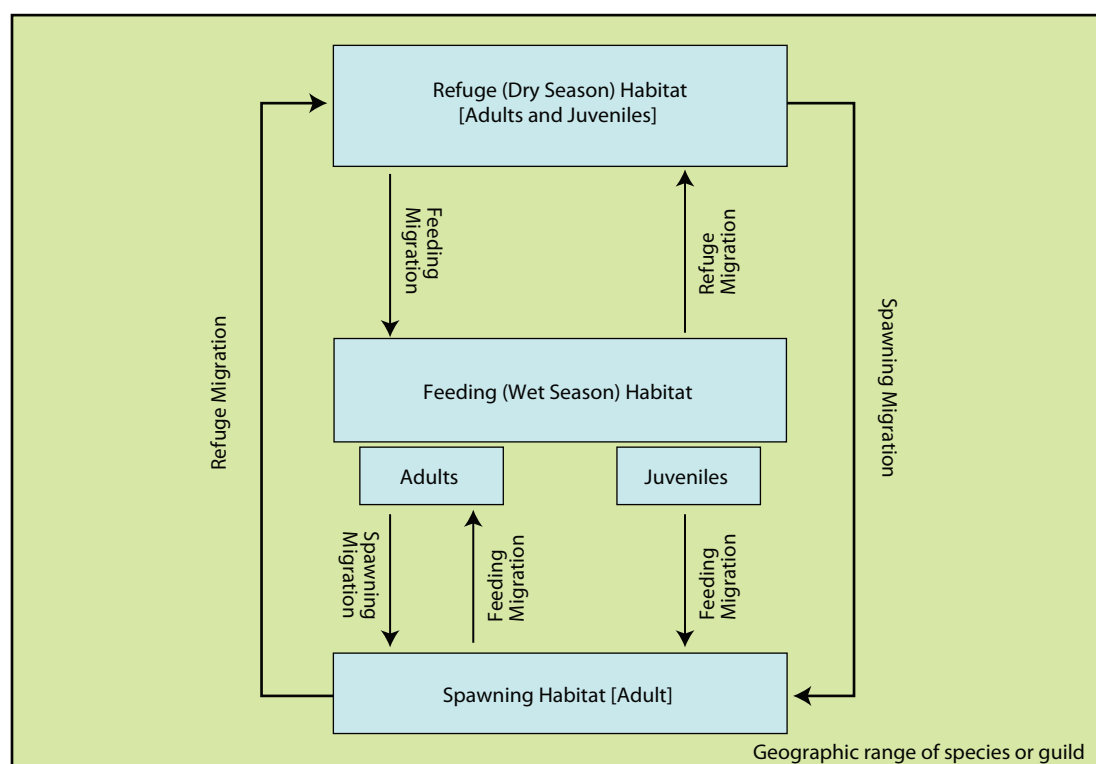


Figure 1.3 Study approach and report structure.

2. Method

2.1 Species at risk

As discussed in Chapter 1.2 above, not all species of fish caught in the basin will be threatened by mainstream dams. Species of fish most likely to be impacted will be those that undertake significant (passive and active) migrations within the mainstream between critical habitats as part of their life history strategy. Three main categories of critical (or functional) habitat can be identified: Spawning, feeding, and refuge (Figure 2.1).



Redrawn and modified from Lucas & Baras 2001

Figure 2.1 Schematic representation of potential fish migrations between critical habitat.

For impact modelling purposes, it is useful to identify major categories or types of migratory behaviour exhibited by fish species inhabiting the lower Mekong basin. For the purposes of this research, we describe these categories as 'Migratory guilds'. This guild concept helps facilitate the identification of species within the assemblage that are most likely to be impacted by hydropower development. The likelihood of impact for each guild will be largely determined

by the extent to which the mainstream acts as a conduit or migration corridor for each major life history stage between critical habitats.

We propose 10 migratory guilds of fish based upon their migrations or exchanges of life history stages between critical habitat via the mainstream (Table 3). These represent variants or aggregations of the environmental guilds proposed by Welcomme *et al.* (2006). The differences reflect the impact pathway under examination i.e. barrier and passage effects compared to modified flow effects, but also current understanding of the ecology of fish in the LMB.

The migrations and therefore the viability of populations of species belonging to guilds 2, 3, 8 and 9 (and to a lesser extent guild 4) are most threatened by hydropower dams in the mainstream.

Identification of species belonging to each guild.

Species of fish that are likely to belong to each of the 10 guilds described in Table 2.1 were identified on the basis of their presence or absence as adult and larvae/juvenile stages within riverine and floodplain habitats of the system as recorded by MRC monitoring programmes, ad hoc surveys, as well as on the basis of information contained in the Mekong Fish Database (MFD) and wider literature. A Venn diagram (Figure 2.2) was developed to help deduce species groupings by guild based upon the available data sets.

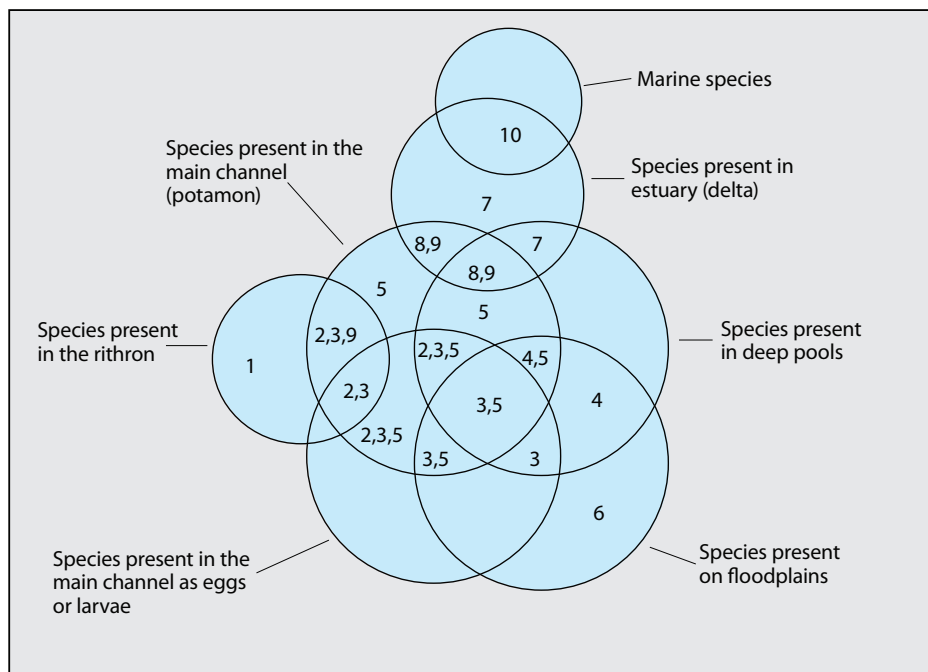


Figure 2.2 Venn diagram illustrating the identification species belonging to the migratory guilds of fish based upon the presence or absence of their adult or juvenile stages sampled within riverine and floodplain habitats.

Table 2.1 *Migratory guilds proposed for mainstream dam impact forecasting. Highly vulnerable guilds are shaded blue.*

Migratory guild	Potential range of habitat utilised	Typical characteristics*	Likely impact of mainstream dams on migrations.
1. Rithron resident guild	Rithron	- Resident in rapids torrents, rocky areas and pools in the rithron. - Generally insectivorous, algal scrapers or filter feeders, small in size, lithophilic or phytophilic with extended breeding seasons and suckers or spines to maintain position in the flow - Limited migrations.	Little or no impact
2. Migratory main channel (and tributaries) resident guild	Marine to Rithron	- Long distance migrants spawning in the main channel (sometimes in rithron) upstream of adult feeding habitat in the main channel. - May migrate to refuges (deep pools) in the main channel during the dry season. - Pelagophilic members have drifting pelagic egg or larval stages returning to adult habitat utilising backwaters and slacks as nurseries. - Adults do not enter floodplain and may be piscivorous. - Lithophilic members may be anadromous with fry resident at upstream site for a certain period and may occupy upstream floodplain. - May also include psammophils (sand spawners). - Members vulnerable to overexploitation and tend to disappear when river is dammed preventing longitudinal upstream migration. May respond favourably to fish passage facilities. - Includes anadromous species.	Very high
3. Migratory main channel spawner guild	Floodplains to Rithron	- Spawn in the main channel, tributaries or margins upstream of floodplain feeding and nursery habitat often with pelagic egg or larval stages. - Pelagophilic, lithophilic, phytophilic (in floodplain margins) or psammophilic. - Adults and drifting larvae return to floodplains to feed. - May migrate to refuges (deep pools) in the main channel during the dry season. - Tend to disappear when river is dammed preventing longitudinal migrations to spawning and refuge habitat.	Very high

Migratory guild	Potential range of habitat utilised	Typical characteristics*	Likely impact of mainstream dams on migrations.
4. Migratory main channel refuge seeker guild	Floodplains to potomon	- Undertake migrations from floodplain feeding and spawning habitat to refuges (deep pools) in the main channel during the dry season. - Predominantly phytophils. - Differ from main channel spawner in that spawning occurs on the floodplain with main channel used as refuge during dry season. - Threatened when river is dammed preventing lateral and longitudinal migrations to refuge habitat in main channel.	Medium
5. Generalist guild	Floodplains and potomon	- Limited non-critical migrations in mainstream. - Highly adaptable, mobile and static elements in their genome make them highly adaptable to habitat modification. - Often repeat breeders or breed during both wet and dry seasons sometimes with nests and parental care. - Rheophilic or linnophilic; often tolerant of low dissolved oxygen concentrations - May be semi-migratory often with sedentary local populations. - Benthic members are predominantly lithophils and psammophils and occupy centre of main channel with intolerance to low dissolved oxygen. May seek refuge in deep pools during dry season. - The riparian zone members typically occur amongst the vegetation of the main channel and fringing floodplains. - May undertake lateral migrations to floodplain to occupy similar habitats during flooding. - Often tolerant and low dissolved oxygen and exhibit wide range of breeding behaviour but predominantly phytophils. - This guild is especially well represented in most rivers.	Little or no impact

Migratory guild	Potential range of habitat utilised	Typical characteristics*	Likely impact of mainstream dams on migrations.
6. Floodplain resident guild (Blackfish)	Floodplains	- Limited migrations between floodplains pools, river margins, swamps, and inundated floodplains. - Tolerant to low oxygen concentrations or complete anoxia. - Little or no impact - Often repeat breeders, phytophils, nest builders, parental care or live bearers.	Little or no impact
7. Estuarine resident guild	Estuary	- Limited migrations within the estuary in response to daily and seasonal variations in salinity. - Brackish water guild euryhaline and usually confined to brackish part of system. - Freshwater estuarine guild includes stenohaline species that inhabit freshwater component of estuarine system.	Little or no impact (if dam is upstream of estuary and does not influence salinity dynamics in estuary).
8. Semi-anadromous guild	Estuary and lower potomon	- Enters fresh/brackish waters to breed - Enters freshwaters as larvae/juveniles to use the area as a nursery, either obligate or opportunistic. - Impacted by river mouth dams that stop migration into the river.	High (for dams located in river mouths or lower potomon).
9. Catadromous guild	Marine to Rithron	- Reproduction, early feeding and growth at sea. - Juvenile or sub-adult migration to freshwater habitat often penetrating far upstream. Members vulnerable to over exploitation and tend to disappear when river is dammed preventing longitudinal upstream migration. May respond favourably to fish passage facilities.	Very high
10. Marine guild	Estuary	Enters estuaries opportunistically	Little or no impact

*Note: *often drawing heavily from Table II of Welcolme *et al.*, (2006)*

Species present in the, main channel, floodplain and estuarine habitats

The presence (or absence) of fish species in main channel, estuary and floodplain habitats, and their relative abundance based upon landed weights, was determined from daily logbook catch records of fishers located at 40 sites along the length of the mainstream and fringing floodplains from Bokeo in northern Lao PDR to the Vietnamese Mekong Delta for the MRC's Assessment of Mekong Capture Fisheries Programme (Figure 2.3). Only data for the 12 month period December 2003 to November 2004 were included corresponding to the period of maximum spatial and temporal data coverage.

Species present in the main channel as eggs or larvae

These species were identified from their presence in fish larvae monitoring surveys undertaken in Viet Nam in 2000 described by Du *et al.* (2008) and in Cambodia during 2006 described by Tarith & Halls (2008) (Figure 2.3). These survey years were selected based upon data availability from research institutions and survey duration. At the time of reporting, no comparable data were available for Thailand or Lao PDR.

Species present in deep pools

Species present in deep pools (and their relative abundance measured in terms of catch rates [CPUE]) was determined from pilot surveys of fish biomass and abundance in a sub-sample of 10 deep pools in the Mekong described by Halls (2008).

Floodplain resident species

A list of species belonging to Guild 6 (floodplain resident species or blackfish) was compiled from the listings of blackfish species contained in AMCF database (species look-up table). Little ambiguity exists when identifying these species because they typically possess morphological adaptations for surviving the harsh environmental conditions which exist on the floodplain during the dry season.

Marine species

Similarly, a list of marine species forming Guild 10 was compiled from the same species look-up table contained in the AMCF database.

A database containing the species lists (and relative abundance data) described above was compiled using Microsoft Access software. Species scientific names and codes were first checked and corrected for duplicates, synonyms and misidentifications. The correct scientific names and codes were assumed to be those contained in the MFD and the AMCF database species-look up table.

The database was then queried to identify each sub-set of species illustrated in Figure 2.2. Marine species (Guild 10) were first removed from the list of species recorded as present in

the catches taken from the main channel, floodplain and estuary (delta). Species present in the catches landed from main channel in Viet Nam but not in Cambodia (or elsewhere upstream) were assumed to belong to the estuarine-resident guild (Guild 7) and therefore removed since none of the planned dam locations are within the delta. Floodplain resident species (Guild 6) were also removed since they typically do not undertake obligatory longitudinal migrations in the main channel.

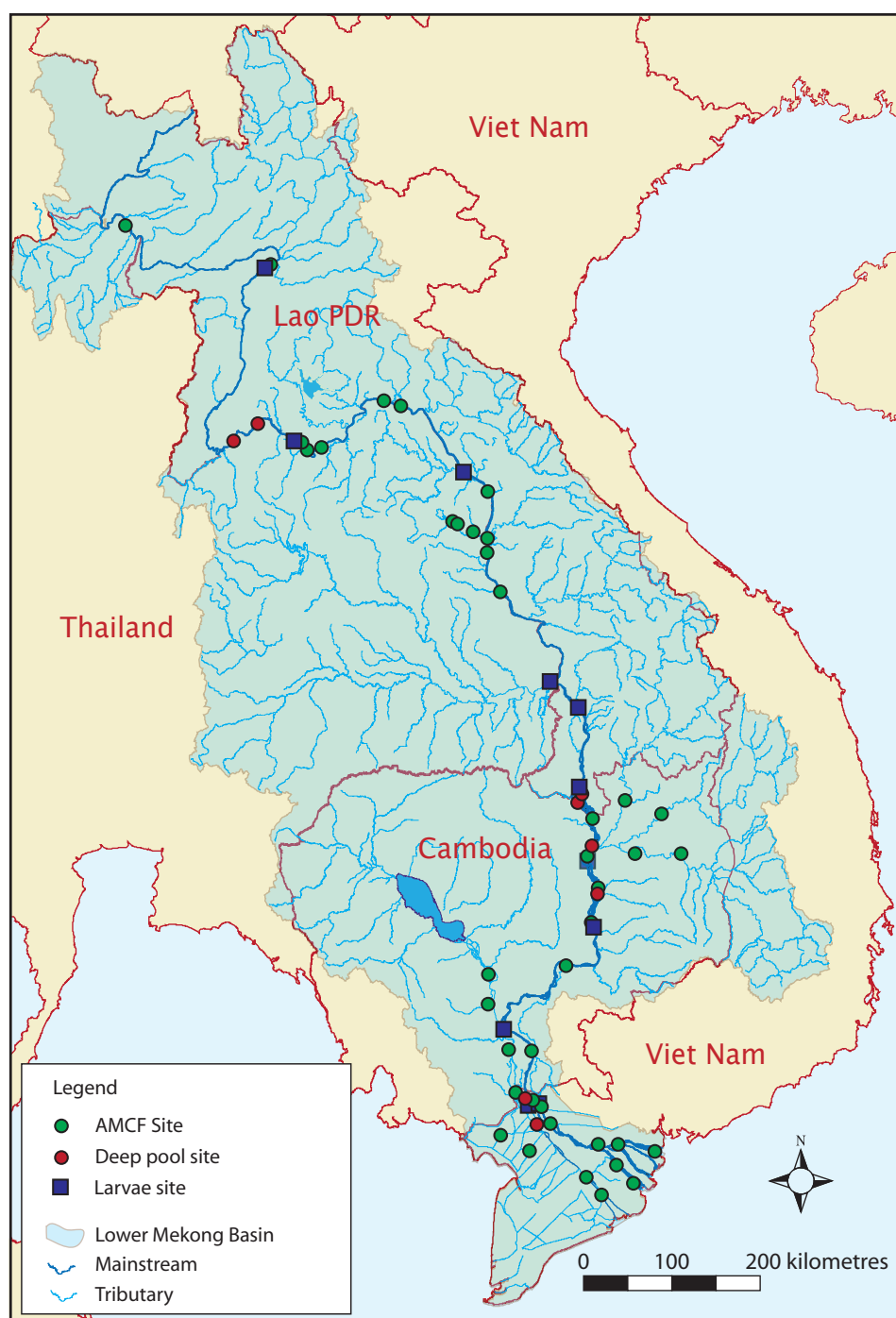


Figure 2.3 Site locations of AMCF fisher-catch surveys, AMCF/FEVM fish larvae monitoring programmes, and FEVM deep pool survey sites.

For those sub-sets of the Venn diagram containing species potentially belonging to more than one guild, a judicious approach was adopted to assign each species to the appropriate guild. This process was guided largely by the information relating to the ecology, spawning migrations and distribution of the species described in the MFD and Poulsen *et al.* 2004.

A total of 233 species of fish belonging to 55 families were reported by the AMCF survey as present in the main channel, floodplains and estuary. This included 19 marine species belonging to 16 families. Twenty-two species of blackfish belonging to 9 families were identified. A further 42 species belonging to 17 families were found only in the Vietnamese Mekong Delta. The remaining 150 species were identified as whitefish belonging to guilds 1–5, 8 and 9 (Table 4).

Fifty-eight whitefish species were assigned to the highly vulnerable guilds (Appendix 1). They include 5 of the 11 Mekong fish species threatened by extinction according to the IUCN ‘Red List’ (<http://www.redlist.org>): the Mekong giant catfish (*Pangasianodon gigas*), the Mekong stingray (*Dasyatis laosensis*), Jullien’s barb (*Probarbus jullieni*), the Laotian shad (*Tenualosa thibaudeaui*) and the Thicklip barb (*Probarbus labeamajor*).

A further 26 species belonging to the ‘floodplain spawner’ guild were identified as being at medium risk of impact. The 58 species belonging to the highly vulnerable guilds (2, 3, 8 and 9) contributed to 38.5% of the total weight of all 233 species recorded in the fisher catch survey in 2003/04 (Table 2.2).

Table 2.2 Number of species belonging to each guild and their relative contribution to the total catch recorded by the AMCF survey, Nov 2003–Dec 2004.

Guild	Guild name	Species	Catch (kg)	% catch
1	Rithron resident	6	190	0.16
2	Main channel resident	38	18 694	15.37
3	Main channel spawner	14	26 160	21.51
4	Floodplain spawner	26	17 945	14.76
5	Generalist	56	43 203	35.53
6	Floodplain resident (Blackfish)	22	6251	5.14
7	Estuarine resident	42	5773	4.75
8	Semi-anadromous	3	81	0.10
9	Catadromous	3	1865	1.50
10	Marine	19	1290	1.06
	Unknown	4	155	0.13
	Grand Total	233	121 607	100.00

After removing minor species (representing less than 0.5% of the total sample catch weight), it was found that guilds vulnerable to mainstream dam development (2,3,8, and 9) comprised 32 species (or only 20 species comprising 32% of the total weight if a 1% cut-off is used). By far the most important families were Cyprinidae and Pangasiidae (Table 2.3).

Table 2.3 *Recorded fisher catch weights by family for guilds 2,3,8,9 only.*

Family	Catch (kg)	%
Cyprinidae	29 166	24.0
Pangasiidae	9835	8.1
Gyrinocheilidae	1976	1.6
Palaeomonidae	1854	1.5
Cynoglossidae	1606	1.3
Cobitidae	1403	1.2
Sisoridae	369	0.3
Schilbeidae	298	0.2
Dasyatidae	116	0.1
Soleidae	68	0.1
Clupeidae	46	0.0
Engraulidae	35	0.0
Siluridae	15	0.0
Megalopidae	9	0.0
Anguillidae	2	0.0
All Guilds (233 species)	121 606	38.5

Table 2.4 *Families of fish belonging to guilds 2,3,8,9 selected for impact modelling highlighted bold.*

Guild	Family	Catch (kg)	% catch (all guilds)
2	Cobitidae	106	0.1
	Cynoglossidae	1606	1.3
	Cyprinidae	4304	3.5
	Dasyatidae	116	0.1
	Gyrinocheilidae	1976	1.6
	Pangasiidae	9835	8.1
	Schilbeidae	298	0.2
	Siluridae	15	0.0
	Sisoridae	369	0.3
	Soleidae	68	0.1
	Sub Total	18 694	15.4
3	Cobitidae	1298	1.1
	Cyprinidae	24 862	20.4
	Sub Total	26 160	21.5
8	Clupeidae	46	0.0
	Engraulidae	35	0.0
	Sub Total	81	0.0
9	Anguillidae	2	0.0
	Megalopidae	9	0.0
	Palaeomonidae	1854	1.5
	Sub Total	1865	1.5
All guilds		12 1607	100.0

Within each vulnerable guild (2, 3, 8, and 9) families of fish contributing to more than 1% of the total fisher catch for the 12 month AMCF survey period were selected for impact modelling (Table 2.4). This excluded species belonging to the semi-anadromous Guild 8. Together the 6 families comprised 98 % of the catch of the vulnerable guilds and 38% of the survey catches for all guilds combined.

Species belonging to each of the 7 guild-family combinations identified in Table 2.4 were then selected for impact modelling. The most abundant species (judged in terms of their contribution to the survey catches) within each combination were selected in addition to species of significant conservation or commercial interest (Table 2.5). These 12 species contribute to 67 % of the recorded catch for species identified as highly threatened by mainstream dam development (Guilds 2,3,8, and 9) and 26% of the recorded catch for all species recorded in the AMCF survey for the period Nov 2003 to Dec 2004.

Table 2.5 *Species selected for impact modelling.*

Guild	Family	Species	Code	Catch (kg)	% of Guilds (2,3,8,9)	% all Guilds
2	Cynoglossidae	<i>Cynoglossus microlepis</i>	136	1606	3.43	1.32
	Cyprinidae	<i>Hypsibarbus malcolmi</i>	44	1798	3.84	1.48
	Cyprinidae	<i>Probarbus jullieni</i>	23	330	0.71	0.27
	Gyrinocheilidae	<i>Gyrinocheilus pennocki</i>	75	1976	4.22	1.63
	Pangasiidae	<i>Pangasius conchophilus</i>	102	2516	5.38	2.07
	Pangasiidae	<i>Pangasianodon gigas</i>	109	13	0.03	0.01
3	Cobitidae	<i>Botia helodes</i>	79	849	1.81	0.70
	Cyprinidae	<i>Henicorhynchus lobatus</i>	62	4946	10.57	4.07
	Cyprinidae	<i>Henicorhynchus siamensis</i>	63	9838	21.02	8.09
	Cyprinidae	<i>Cosmochilus harmandi</i>	27	3489	7.46	2.87
	Cyprinidae	<i>Paralaubuca typus</i>	11	2013	4.30	1.65
9	Palaeomonidae	<i>Macrobrachium rosenbergii</i>	192	1854	3.96	1.52
Total				31 227	67.00	26.00

Basin-wide landings and value at risk

Combining the proportion of the landed catch attributable to the highly vulnerable species (38.5%) described above with recent estimates of the total catch of all species from the basin (1,860,000 tonnes) reported by Hurtle (2007), we estimate that approximately 0.75 million tonnes of fish are vulnerable to mainstream dam impacts worth in excess of US\$1.4 billion assuming a unit value of \$1.89 kg⁻¹ as used by Barlow *et al.* (2008).

However, it should be borne in mind that the analysis described above was primarily undertaken to select species of fish whose migrations are likely to be effected by mainstream dam development. Whilst the AMCF catch survey data provides some objective basis for determining the relative importance of the threatened species in basin, the estimates may be biased given that the majority of the reported landings contained in the database were for gillnet

fishers targeting mainstream habitat. It does not, for example, include landings from industrial-scale or specialised fisheries such as the Cambodian bagnet fishery in the Tonle Sap River that targets migratory species seeking refuge habitat (believed to be located near the boarder with Lao PDR) during the falling water period. Nor does it include the 'lee trap' fisheries of the Khone Falls in southern Lao PDR that target the upstream spawning migrations of fish. Including such fisheries would likely raise the estimate of the proportion of the basin's catch threatened by dam development. However, at the same time, the AMCF survey is unlikely to have representatively sampled landings of floodplain-resident species or generalists from floodplain systems such as the Songkhram system in Thailand, which would have the opposite effect on the estimates.

A more accurate assessment of how much of the catch from the LMB is threatened by mainstream dam development will require unbiased estimates of the relative contribution of the threatened species identified above to the entire landings within the basin. This will require a carefully-designed basin-wide and species-wise household or fisher-based catch assessment survey with appropriate stratification to account for temporal, spatial and habitat-dependent variation in species abundance (catches).

It should also be borne in mind that the estimate of the proportion of the basin's catch that is threatened by mainstream dam development derived using the AMCF survey data above relates only to the barrier effects of dams on fish migrations. It does not include the modified flow effects including changes to habitat availability and quality and is therefore likely to be conservative estimate of potential loss.

Furthermore, the value estimate above does not take into account the economic benefits that flow from the trade and processing of fish products. Nor does it include the very considerable indirect values of the Mekong fisheries, such as their contribution to the nutrition, employment and well-being of millions of rural people in the LMB, who generally have few other livelihood options.

Fish life cycles and migrations

The model described below attempts to simulate the barrier and passage effects of mainstream dams on fish populations as they attempt to complete their life cycles involving significant bi-directional longitudinal migrations between spatially-separated critical or functional habitats. Detailed information about the life cycles of the species selected for modelling is sparse and therefore we generalize these based upon the behaviour of the guilds to which they belong (see summary in Table 2.3 and a generic model of floodplain river fish life-cycles (Figure 2.4) after Lowe-McConnell (1975).

In the model described below, sexually mature adults of species belonging to the vulnerable Guilds 2 and 3 undertake longitudinal migrations from dry season refuge habitat to upstream spawning habitat during the rising flood period before returning with their progeny (juvenile fish) to downstream feeding, nursery and refuge habitat (Figure 2.5, a and b). The period between leaving the refuge habitat and returning to downstream feeding habitat is assumed to be three months (approximately month 6–9 in Figure 2.4). Immature fish present in the refuge habitat fish move directly to feeding habitat where they remain feeding and growing for 10 months. Adults and young-of-the-year (YoY) returning from upstream spawning locations (Figure 2.5, c) remain in the feeding habitat for 7 months (until approximately the end of month 3 in Figure 2.4). All fish then move to the refuge habitat (Figure 2.5, d) and remain there for two months (months 4 to 5 in Figure 2.4), before the cycle is repeated. This iteroparous life cycle where adult fish may spawn several times during their lifetime to maintain viable populations contrasts with that of semelparous species exemplified by Pacific salmon (*Oncorhynchus* genus) where adult fish die after spawning. All model species have been reported to inhabit deep pools (Halls *et al.*, in prep.) at some time of the year, and all except *P. gigas* were recorded in quantitative depletion surveys of deep pools during March 2008 (Halls *et al.*, 2008).

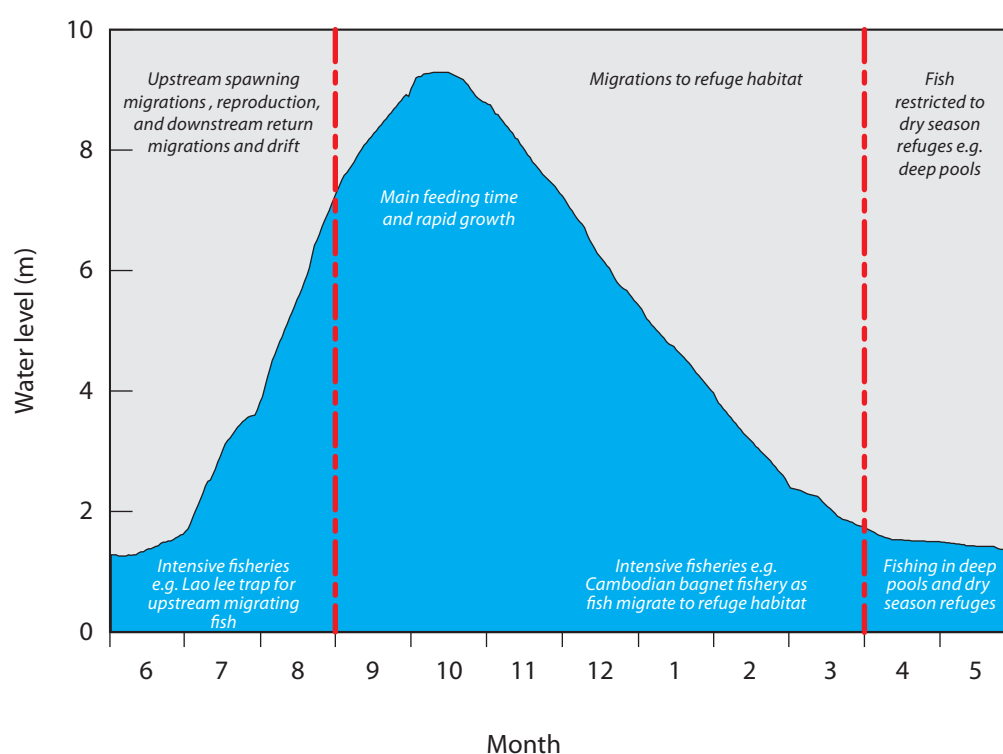


Figure 2.4 Generic life-cycle model of floodplain-river fish in the Mekong River (after Lowe-McConnell, 1975). Water level is for the period 01/06/2005 until 31/05/2006 at Kampong Luong, Cambodia.

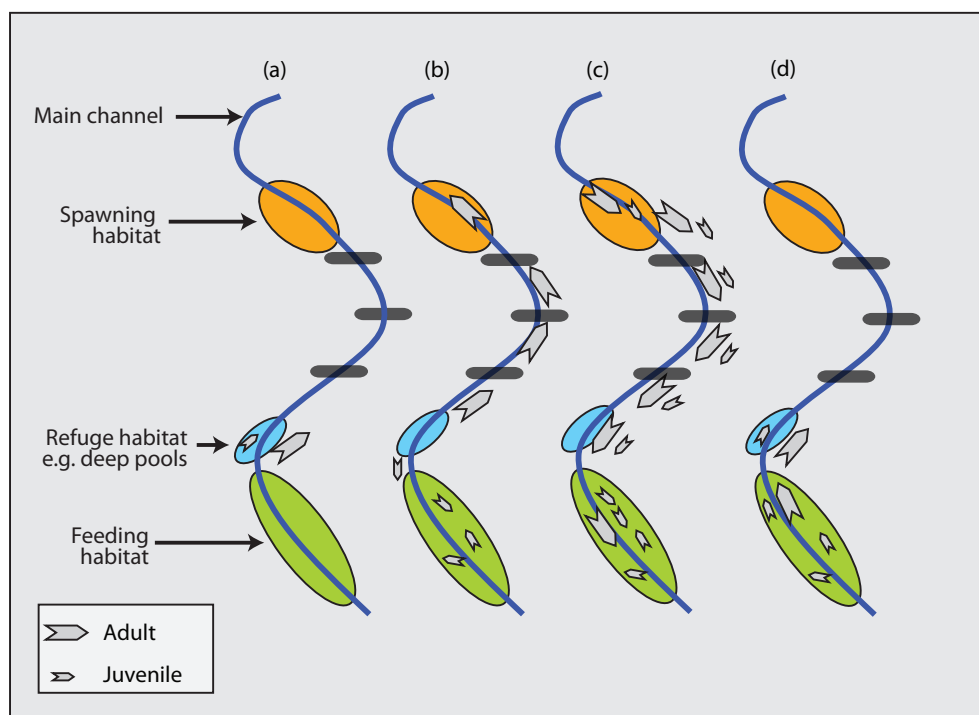


Figure 2.5 Graphical illustration of the life cycle of the fishes described by the model and assumptions regarding habitat distribution relative to the dam locations.

Attempts were made to identify approximate spawning periods for each species using the AMCF catch data set described above by plotting temporal (monthly) changes in mean fish weight and individual number of fish (see Appendix 2 for example plots). Rapid declines in mean fish weight followed by a rise in the number of individual fish landed were interpreted to correspond to the approximate spawning period. These periods corresponded closely with those reported in the MFD (Visser, 2003).

For eight of eleven species for which data were available, the spawning period ranged from May to August which is in agreement with the general life-cycle illustrated in Figure 2.4. *Hypsibarbus malcolmi* and *Probarbus jullieni* appear to spawn in December whilst no obvious single spawning period could be identified for *Macrobrachium* spp (assumed to be *rosenbergii*). It may be that this shrimp species is a repeat spawner as suggested by Cavallo *et al.* (2007). In the model, *H. malcolmi* and *P. jullieni* are assumed to share the same life-cycles since the spawning month specified in the model has no effect on the study conclusions. The plots also indicate that the fish species spawn only once as assumed in the model.

Knowledge of the life-cycle of adult *Macrobrachium rosenbergii* in the LMB is sparse but understood to include bi-directional migrations of up to 200 km or more (Pantulu, 1986) to upstream feeding habitat as adults (and sub-adults) that return downstream to spawn in brackish waters in river estuaries. There are reports of *Macrobrachium* species caught upstream of Khone Falls, in the Mun River, Thailand, and in several locations in Lao PDR, but these may have been locally stocked (Kent Hortle, pers. comm.). In the river estuaries, eggs hatch as free-swimming

larvae. Before metamorphosis into post-larvae (PL), the planktonic larvae pass through several zoeal stages. After metamorphosis, the PL assumes a more benthic life style and begins to migrate upstream towards freshwater (FAO 2002). Accounts of fisheries in Cambodia (Ngor *et al.*, 2005) indicate that this shrimp feeds in upstream floodplain habitat during the flood season and migrates towards the Vietnamese part of the Mekong Delta to spawn between January and May. Upstream feeding migrations are therefore likely to occur between June and July consistent with reports from other river systems (Chan-Lui Lee, pers. comm.).

This life cycle and timing of major events may therefore not be dissimilar to those species belonging to Guilds 2 and 3, except that their spawning habitats are downstream not upstream of their feeding habitats. However, unlike Guilds 2 and 3, juvenile (as well as adult) *Macrobrachium* must attempt to pass dams during upstream migrations, and only adults are likely to return downstream through turbines, spillways and other bypasses.

Whilst including these dynamics in the model described below would provide insights into how catadromous species may behave in response to mainstream dam development in the LMB compared to the species belonging to Guilds 2 and 3, no body size-dependent functions to describe shrimp survival required for the model below could be found in the literature. This is regrettable since despite the small contribution this species makes to the overall basin-wide landings, it is economically important with unit market values in excess of \$10 kg⁻¹. It also is the only catadromous species included in the study. We therefore recommend that any future model development include this species to determine if populations of catadromous species respond in the same manner to barrier and passage effects as species belonging to Guilds 2 and 3.

Species range and spatial distribution of critical habitat

We examined spatial and temporal variation in the relative fish abundance indicated by fisher catch rates recorded under the AMCF survey in an attempt to determine the spatial range of the model species and the distribution of their critical habitats. Spatial distribution was examined in terms of longitudinal distance in the mainstream channel measured from the mouth of the Mekong in the Vietnamese part of the Mekong Delta.

The population range was determined from the minimum and maximum distance within which the population was detected (present) in daily fisher catch rates, irrespective of gear type (i.e. CPUE > 0) at the 40 monitoring locations.

The analysis confirmed the very wide range of the model species in the LMB (Figure 2.6). Eight of the 12 species are present almost throughout the length of the LMB based upon the survey results. The survey data does not adequately represent the range of *P. gigas* (species code 109) which is regularly caught as far upstream as Chiang Khong/Huay Xai in northern Thailand and Lao PDR, some 2400 km from the sea and upstream of all the proposed dam sites in the LMB (Lorenzen *et al.*, 2006). This location is believed to be a major spawning location and therefore access to it is essential to the survival of the population (ibid). *Macrobrachium rosenbergii* may also be landed beyond the upper range illustrated in Figure 2.6 because this

species is not included in species identification catalogues issued to fishers participating in the AMCF catch survey. The exception appears to be the small-scale tongue sole *Cynoglossus microlepis* that is restricted to locations downstream of Khone Falls. The results are consistent with the species distributions reported by Poulsen *et al.* (2004) although *Probarbus jullieni* is believed to have a much wider range than indicated from the catch data alone (see Appendix 4).

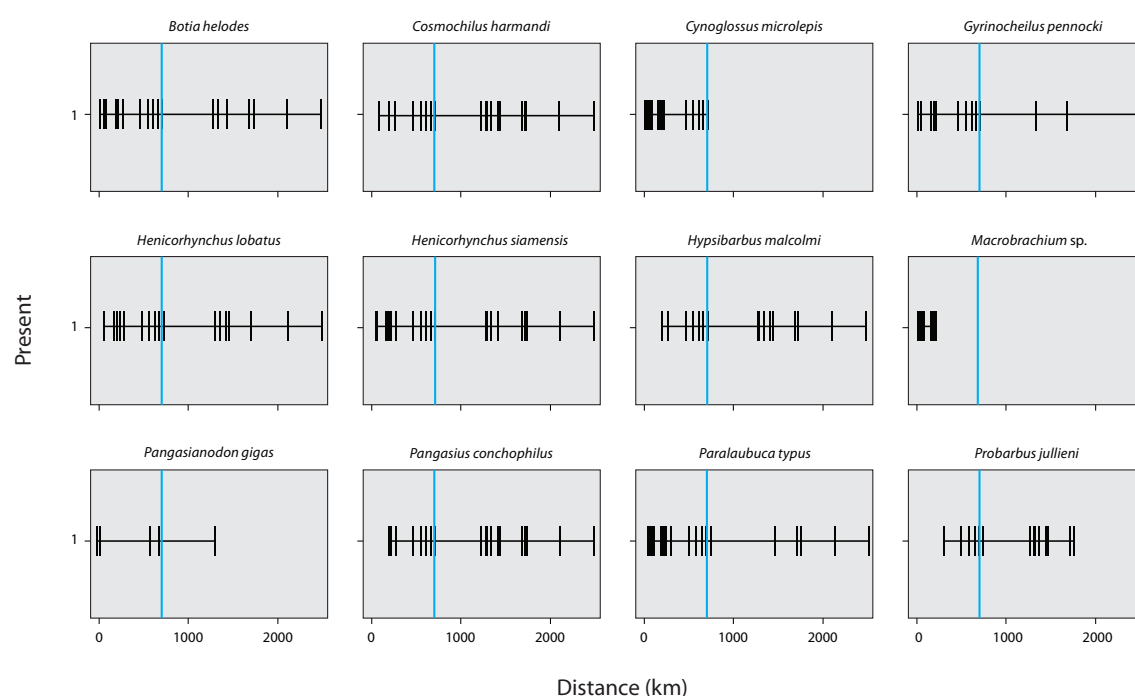


Figure 2.6 The estimated population range of each species along the Mekong mainstream based upon fisher landings. The small vertical bars illustrate the position of the monitoring sites where the species was caught during the survey period. The full vertical line illustrates the approximate location of the proposed Don Sahong hydropower dam at the Khone Falls (719 km).

Table 2.6 The approximate range of populations of the model species.

Species	Code	Lower limit (km)	Upper limit (km)	Range (km)
<i>Cynoglossus microlepis</i>	136	9	707	698
<i>Hypsibarbus malcolmi</i>	44	183	2488	2305
<i>Probarbus jullieni</i>	23	217	1719	1502
<i>Gyrinocheilus pennocki</i>	75	9	2488	2479
<i>Pangasius conchophilus</i>	102	183	2488	2305
<i>Pangasianodon gigas</i>	109	14	1335	1321
<i>Botia helodes</i>	79	9	2488	2479
<i>Henicorhynchus lobatus</i>	62	46	2488	2442
<i>Henicorhynchus siamensis</i>	63	46	2488	2442
<i>Cosmochilus harmandi</i>	27	81	2488	2407
<i>Paralauca typus</i>	11	9	2488	2479
<i>Macrobrachium rosenbergii</i>	192	9	217	208

Attempts to identify the approximate location and range of the critical habitat of each species were also made by examining the distribution of model species abundance (as indicated by CPUE) along the mainstream corresponding to the periods (months) when the species is assumed to be occupying each critical habitat according to the life-cycles described above.

These attempts were largely unsuccessful possibly because of the incomplete and sparse coverage of the basin by the AMCF survey, small sample sizes, as well as discontinuities in survey activity. **We therefore made the simplifying assumption that all spawning habitat is distributed upstream of the dam locations as illustrated in Figure 2.5.**

Refuge habitat

Refuge habitat in the form of deep pools is distributed throughout the entire length of the Mekong mainstream, although the deepest pools are clustered around the same locations as the proposed dam locations (Figure 10). Deep pools are also common in tributaries of the Mekong.

Research is currently underway to identify the distribution of important deep pool refuge habitat based upon fish biomass and diversity surveys (for details, see Halls, 2008). Until the results of the research are available, the model predictions described below assume that access to deep pool habitat is not diminished by the proposed dams and therefore does not affect dry season fish survival rates. However, the model can accommodate other assumptions about the distribution of this critical habitat relative to the proposed dam locations and other critical or functional habitat.

Pools upstream of dams are at risk of being filled with sediment, while pools with alluvial substrate immediately downstream of dams may deepen. For the upstream case, each dam will create a backwater effect which may impact on upstream functional habitats, the magnitude of which will depend on the design height of the dam wall. The likely impacts of these flow modification effects on the quality of this refuge habitat and its dependent fish populations are discussed further in Halls *et al.* (in prep).

Feeding habitat

Workers including Lowe-McConnell (1975) and Nikolsky (1937) have proposed that a linear succession of dominant foods sources exist in rivers and streams. Fishes in headwaters mostly utilise allochthonous foods falling or washed into the water from the terrestrial system. These are succeeded by benthic invertebrates as the stream enlarges. Finally in the lower reaches, detritus and soft mud form major food items as well as fish for piscivorous predators (Welcomme, 1985).

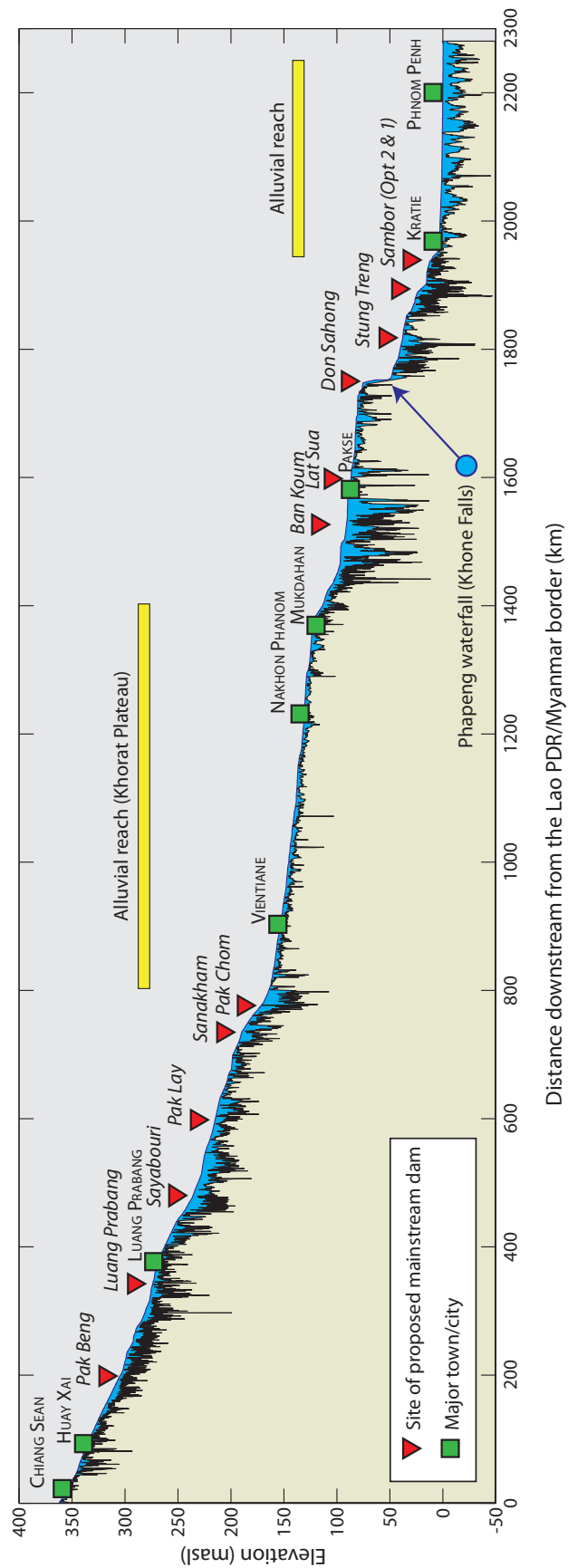


Figure 2.7 Location of proposed hydropower dams in relation to the long-profile of the lower-Mekong riverbed and dry season water surface. Source: Halls *et al.* (in prep).

River fish exhibit highly facultative feeding behaviour with many species able to switch diets both seasonally and spatially according to resource availability and relative nutritional benefit of individual items (ibid). Moreover, given the sparsity of knowledge of the diet and feeding behaviour of the model species, we made the simplifying assumption that feeding habitat is downstream of spawning habitat and the sites of dams included in the model (Figure 2.5). The model can however accommodate other assumptions about the distribution of feeding habitat relative to other habitats and the location of proposed dams. In the case of the palaeomonid shrimp (*Macrobrachium rosenbergii*), adult feeding habitat is assumed to lie upstream of the proposed dam sites.

Recommendations for examining alternative assumptions about the relative distribution of spawning and other functional habitats in relation to the proposed position of the mainstream dams, and habitat fragmentation effects are discussed in Chapter 4.1.

Assumptions about population structure

Fish population structure and the distribution of critical habitat relative to the proposed locations of the mainstream dam sites will largely influence the degree of barrier and passage effects on fish populations and their fisheries. Migrations of populations between critical habitats will determine the distribution and occurrence of species within the basin.

The present study makes the simplifying assumption that each model species comprise a single population although alternative assumptions could be examined using the present model structure. The results of genetic studies for *P. gigas* suggests that this is a reasonable assumption (Lorenzen *et al.*, 2006), but evidence exists that this may not be the case for *Henichorynchus species* (Hurwood *et al.*, 2006). Further studies of the population structure of species belonging to the vulnerable guilds are required before generalizations concerning the validity (or otherwise) of this assumption can be made.

2.2 The dam impact prediction model

Previous modelling studies

Various types of modelling approaches have been developed to explore the impact of dams at the level of fish communities, individual behavior, and population. Statistical models have been used to look at the effect of dam fragmentation on rivers and their impact on species numbers and abundance (Fukushima *et al.*, 2007; Nilsson *et al.*, 2005; Agostinho *et al.*, 2004). Other types of models have looked at particular components of the dam on individuals, such as, the passage rate survival through turbines (Von Raben, 1957), probability of successful navigating through a bypass based on models of fish swimming behavior (Nestler *et al.*, 2008; Goodwin *et al.*, 2007; Weber, 2006; Goodwin *et al.*, 2006), and the impact of flow rates and other environmental variables on migration timing (Zabel *et al.*, 2008; CRiSP, 2000). As an example,

the Columbia River Salmon Passage model (CRiSP) predicts the time it takes for juvenile salmon to migrate through segments of the Columbia and Snake Rivers during their migration to the Pacific Ocean. The model integrates fish cognition and perception of hydraulic patterns to forecast individual swimming behaviour and trajectories through bypass systems. While these models have a potential for broad applications their use has been limited in many cases to make predictions on mortality rate and passage efficiency.

Demographic analysis and matrix population models have been applied to study the impact of dams at population level. A matrix population modelling approach has been built to look at the impact of hydropower systems on population numbers based on empirical estimates of mortality through turbines (Kareiva *et al.*, 2000) and on predictions based on a blade-strike model (Ferguson *et al.*, 2008). The combined blade-strike and life cycle model identifies the effects on fish populations from a dam passage (Ferguson *et al.*, 2008). In this report we further develop the matrix population approach to incorporate seasonal movement between habitats where the complete life cycle of the fish species is completed within a river system and we model downstream passage survival using a turbine-blade strike model (Ferguson *et al.*, 2008; Raben, 1957). Unlike other models using the matrix modelling approach, we use allometric relationships published in the literature to estimate the vital rate parameter of the model. This allows us to model the population dynamics of large numbers of species which in this study in range from 15 cm (*Henicorhynchus lobatus*) to 290 cm (*Pangasianodon gigas*), for an ecological system with high biodiversity of fish species. Finally, this model is designed to study the cumulative dam effects (1–3 dams) with and without exploitation.

General modelling approach adopted for this study

We examined the effects of variable upstream passage success and the effects of downstream passage survival on the population growth rates of the model species (Figure 2.8 and Figure 2.9).

Whilst proposals for up to 11 mainstream dams exist (Chapter 1.1), the inclusion of a maximum of three dams in the model generated sufficient information to illustrate the cumulative effects of multiple mainstream dams on the populations of the species selected for modelling and to quantify the necessary range of minimum mitigation targets to maintain viable populations. The model can, however, include any number of dams.

A length-based projection matrix model (Quinn and Deriso, 1999) was developed to describe the dynamics of each simulated population in response to variable upstream passage success rate via fish ladders or other fish passes and elevated downstream natural mortality rates as they attempt to complete their life cycles. Model ‘transition probabilities’ are estimated by using growth and mortality sub-models.

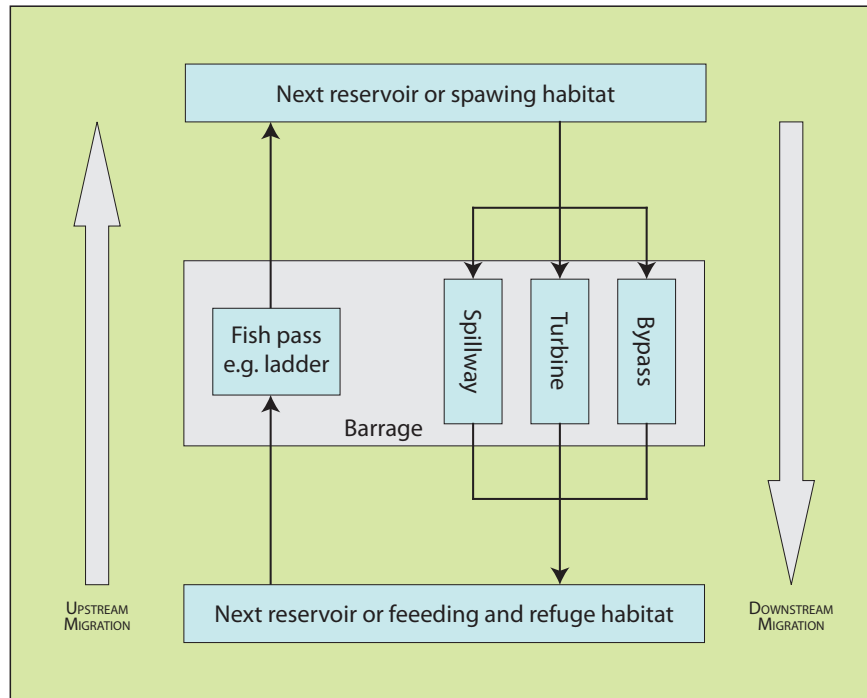


Figure 2.8 Schematic representation of the upstream and downstream migration passage routes included in the model



Figure 2.9 Typical fish passage routes for the upstream and downstream migration at a dam site. During the downstream migration fish leave the fore-bay and pass the dam through spill, bypass or turbine routes. Fish may also be diverted to barges or trucks for transportation. Each route has an associated mortality, determined from experimental tests or different types of model

Migration is modelled by specifying the proportion of individuals that move from one habitat to another in each time step (1 month). These rates form input to a dispersal matrix. Over time, the dispersal rates change from one time step to the next to model the timing of the migration. In cases where there are single or multiple dams obstructing the migration route, the rates are decreased by the fish passage efficiency of the structure.

Such efficiency measure depends on the fish passage route and whether the direction of movement is upstream or downstream. In the case where fish pass through a turbine, the downstream survival rate is estimated using turbine blade-strike model (Ferguson *et al.*, 2008). Upstream fish passage by ladders (or other means, e.g. fish lifts or trap-and transport) depends on the effectiveness of the method employed.

The intrinsic growth rate of the population, λ (lamda) is taken to be a measure of the reproductive potential of the population and can be determined from eigen-value analysis of the matrix based population model. The matrix elements can be adjusted to explore how this measure changes for different fish species, across different dam passage rates and with different level of exploitation.

2.3 Dam passage model

Dam passage models describe the effects of dam structures on passage success and survival of different life history stages. Passage success rate is influenced by the physical characteristics of the dam (e.g. dam height), the efficiency of fish by-pass structures and the operation of the dam which determines the relative volumes of water passing through each flow-through structure.

Our dam passage model is a simplified version of earlier models that incorporate various components such as reservoir survival, fish travel time, predation rate, turbine survival, shear stress, and hydrological process (Zabel, *et al.* 2008).

Upstream passage

Numerous upstream fish passage facilities have been developed with varying degrees of success including pool and Denil-type ladders, nature like by-pass channels, fish lifts, locks, and collection and transportation facilities (Larinier, 2001; Clay, 1995).

Upstream passage success (or efficiency) may be defined as the proportion of the fish that succeed when attempting to pass the dam (Larinier 2008). Experiences from projects worldwide reveal that estimates of upstream passage success rates vary between 0–100% and that they are species-specific (Marmulla, 2001).

It remains uncertain what type of upstream passage facilities might be installed in the proposed dams, other than ladders for which no details are provided, and what their combined

efficiency may be. We therefore modelled the upstream passage efficiency rate as a variable between 0–100%.

Note that in the model adults failing to successfully pass upstream through a dam are returned to the downstream feeding habitat and therefore remain within the population but will not contribute to spawning activity (reproduction) in that model year. Returning adults that failed to pass upstream will experience turbine mortality on their return to the downstream feeding habitat if they have already successfully negotiated at least one dam. Adults that fail to reach the spawning ground above the third dam can experience up to two episodes of turbine mortality.

Minimum efficiency to maintain viable populations was also examined. A viable population is defined as one whose size, measured as the number of individual fish of all length classes, remains stable or increases through time.

Downstream passage

Adult and juvenile fish can pass downstream to feeding and refuge habitat via three main flow-through structures: (i) turbines; (ii) spillways and (iii) by-passes channels (Figure 2.9). The proportion of fish passing via each route depends almost linearly upon the relative volume of water passing through them as demonstrated in Figure 2.10 (Ferguson *et al.*, 2005).

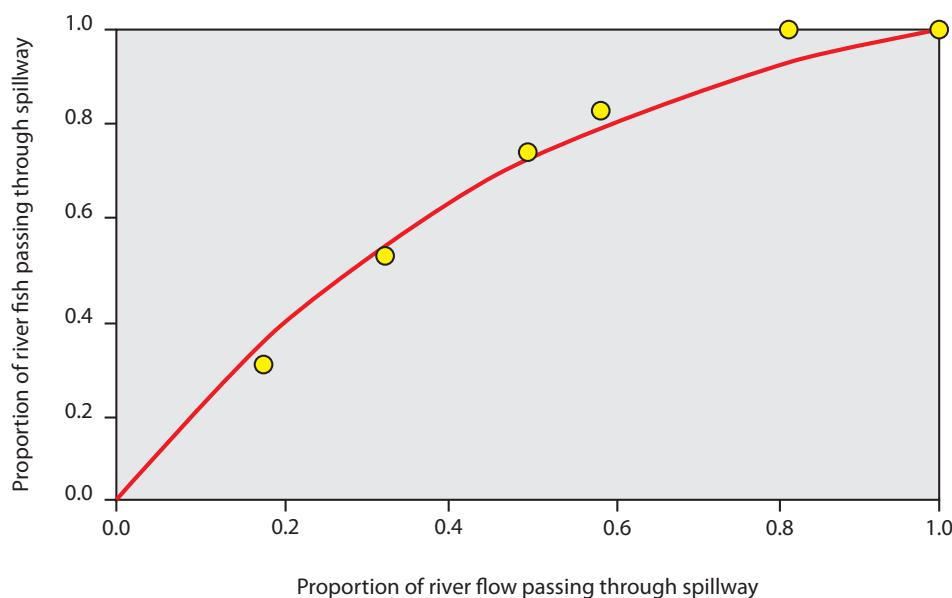


Figure 2.10 Proportion of fish passing through the Lower Granite Dam spillway plotted as a function of the proportion of the Snake River flow passing through the spillway. Source: Zabel *et al.* (2008).

These relative flow proportions remain uncertain at the time of reporting since the proposed dam operating procedures are not publicly available. These procedures will be affected by the presence of other upstream projects or combinations of projects and may vary seasonally according to river flows.

It is likely that power and therefore revenue forgone from flow manipulation and spill via spillways will be minimised since these can be significant. For example, the Bonneville Power Administration that operates the Bonneville Dam on the Columbia River in North America estimates that forgone potential revenue from spilling flow to conserve fish and wildlife is in the order of US\$700 million per annum, equivalent to 30% of total revenue (Williams 2008).

Given these uncertainties, we examine three different scenarios concerning the proportion of the river flow (and corresponding proportion of downstream migrating adult fish) passing through the turbines: 25%; 50%, and 100 %. The remaining proportion of adult fish (75%; 50% and 0% respectively) is assumed to be diverted to spillways or by-pass channels using screens, bars or other diversion structures. For juvenile fish, given their relatively low swimming capacity and limits placed on the minimum mesh size of turbine intake screens, all (100%) of downstream migrating juvenile fish are assumed to pass through the turbines. The model is largely insensitive to this assumption (see Chapter 4). In the Ukraine, Pavlov (1989) reports that 65–91% of all larvae of *Abramis brama*, *Blicca bjoerkna* and *Alburnus alburnus* enter turbine intakes over a period of 3–8 days.

2.4 Downstream passage mortality

Turbine mortality model

Turbine passage is generally considered most likely to injure or kill fish (Schilt, 2007). Effects on fish mortality (survival) rates can be both immediate and delayed (Ferguson *et al.*, 2008).

Delayed mortality is the mortality among fish that experience low levels of physical stress or injury during dam passage and subsequently die from increased susceptibility to disease or predation (Čada, 2001). There has been no attempt to study such effects, but they are likely to be specific to particular species, location and, operation and design characteristics of the dam including the head of water. Mortality rates associated with Francis turbines are generally higher than for Kaplan turbine—typically in the order of 5–90% compared to 5–20%. These differences largely reflect the higher heads of water required for the Francis turbines (Larinier 2001; 2008).

We describe downstream fish mortality (survival) arising from turbine passage using a ‘blade-strike model’. This describes the probability of blade strike and injury to the fish life history stages after the work of Von Raben (1957).

Blade-strike models have been developed for both the Kaplan and Francis turbines (Figure 2.11). All the proposed dam designs include Kaplan type (Table 1.2). The blade-strike model assumes that fish must pass through the plane of the leading edges of the blades in a turbine runner after the sweep of one blade and before the sweep of the next to avoid a strike by a runner blade (Deng *et al.*, 2005).

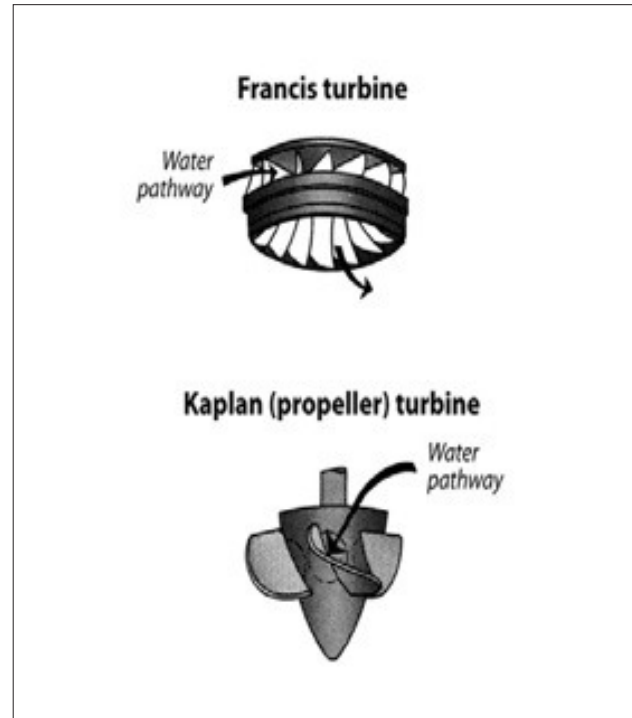


Figure 2.11 Schematic drawings of Francis and Kaplan turbine structures and water pathways (after Ferguson *et al.*, 2008).

For the Kaplan turbine the probability of blade-strike (P_b) is estimated as:

$$P_b = \left(\frac{n \cdot N}{60} \right) \left(\frac{l \cdot \cos \theta}{V_{axial}} \right)$$

where l is fish length (m), V_{axial} is the axial water velocity at the turbine blades, θ is the angle of the fish relative to the blade, n is the number of blades, and N is the rotational rate of the blade in revolutions per minute. The axial velocity is a function of the geometry of the turbine and discharge rate.

For a given turbine design and operational characteristics the probability of a blade-strike increases proportional with fish body length. However, not all strike events result in mortality (Turnpenny *et al.*, 2000). To account for this fact, Von Raben introduced the idea of a *mutilation ratio* (MR). The mutilation ratio is the ratio between the proportion of fish estimated to be struck by a turbine blade and the proportion observed to be injured.

Turnpenny *et al.* (2000; 1998) empirically developed a regression equation of MR for different fish lengths (l , *cm*).

$$MR = \begin{cases} 0.47 & \text{for } W > 200g \\ 0.15533 \cdot \ln(l) + 0.0125 & \text{otherwise} \end{cases}$$

The probability of mortality $M_{turbine}$ from a strike event is estimated as:

$$M_{turbine} = P_b \cdot MR$$

and it follows that the survival probability of passing through a turbine is:

$$S_{turbine} = 1 - M_{turbine}$$

Spillway or by-pass channel mortality

Mortality (both instantaneous and delayed) associated with passage via spillways and by-pass structures has received less attention in the literature. For spillways, mortality estimates for juvenile salmonids range from 0% to 37% (Marmulla, 2001). Damage to fish occurs when free-fall velocity exceeds 16 ms^{-1} achieved by water falling through 13 m. A mortality rate of 100% is expected for drops of 50–60 m. Mortality rates for a given drop increase with fish size (weight). Other determining factors include spillway design and the depth of water at the base of the spillway (Larinier, 2001). Maximum spillway heights of the proposed dams range from approximately 10 m to 40 m with a mean of approximately 25 m (Table 1.2).

Other sources of mortality not included in the model include gas super-saturation effects and increased rates of predation arising from disorientation (Schilt, 2007). These and other possible sources of mortality are ignored in the model. Consequently, estimates of overall downstream passage survival rates are likely to have been overestimated in the model.

2.5 Population dynamics model

Model structure: spatial matrix model

The population model distinguishes between three different habitat types and the seasonal migrations among the critical or functional habitats by different length (age) class individuals. Individuals are modelled to leave the refuge habitat at the end of the dry season or at the onset of the flood season. Mature adults swim upstream to spawning habitat and the juveniles are passed to the feeding habitat. Adults failing to pass a dam via ladders or other passes are returned to the downstream feeding habitat. Adults failing to pass the second and subsequent dams are also exposed to turbine mortality as they return downstream to the feeding habitat.

After spawning, the adults return downstream to feeding habitat. In the spawning habitat, larvae grow into juvenile and begin to drift down the main-stream to the feeding habitat. At the onset of the dry season both adults and juveniles migrate to the refuge habitat that is associated with deep pools within the river channel. This seasonal cycle is repeated annually and is typical of fish species that inhabit the river mainstream. For many species the migration pattern may be repeated several times during their life (see Chapter 2.1).

The matrix population model incorporates habitat-specific vital rates (survival and fecundity rates) and migration success rates between habitat types to model dynamics of fish abundance for different stage or length-classes.

Constructing a spatial matrix model requires specifying the state of the population (the number of individuals in each length class), the demographic characteristics of each habitat, and the dispersal of individuals among the habitats. The population dynamics of a fish population is governed by the following matrix equation:

$$\mathbf{n}_{+1} = \mathbf{A}_t \mathbf{n}_t$$

The population vector, $\mathbf{n}_t$ includes the number of each length class in each habitat type. Specially, the vector $\mathbf{n}_t$ has the entries of $\mathbf{n}_j$ which specifies the number of individuals of stage j at time t which are in the spawning (S), feeding (F) or refuge (R) habitats for each of the q length classes,

$$\mathbf{n}_t = [n_1^S \dots n_q^S | n_1^F \dots n_q^F | n_1^R \dots n_q^R]$$

The projection matrix, $\mathbf{A}_t$, includes both demographic processes, which could differ among habitats and dispersal processes, which may differ among length classes and change with time. The matrix $\mathbf{A}_t$ is the product of the dispersal matrix and the habitat demographic matrix:

$$\mathbf{A}_t = \left[\begin{array}{c|c|c} \mathbf{I} - (\mathbf{M}_t^{SF} + \mathbf{M}_t^{SR}) & \mathbf{M}_t^{FS} & \mathbf{M}_t^{RS} \\ \hline \mathbf{M}_t^{SF} & \mathbf{I} - (\mathbf{M}_t^{FS} + \mathbf{M}_t^{FR}) & \mathbf{M}_t^{RF} \\ \hline \mathbf{M}_t^{SR} & \mathbf{M}_t^{FR} & \mathbf{I} - (\mathbf{M}_t^{RS} + \mathbf{M}_t^{RF}) \end{array} \right] \left[\begin{array}{c|c|c} \mathbf{A}^S & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{A}^F & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & \mathbf{A}^R \end{array} \right]$$

Habitat specific demographic processes for the three habitat types are expressed in the right most matrix. This matrix contains three sub-matrices along diagonal, $\mathbf{A}^S$, $\mathbf{A}^F$, and $\mathbf{A}^R$ specific vital rates and are specific for the spawning (S), feeding (F), and refuge (R) habitat, respectively.

The left matrix is the dispersal matrix. It, too, contains sub-matrices, representing possible movement between different habitat types for each of the length classes. The $\mathbf{M}_t^{ab}$ sub-matrices specify the probability of successfully migrating from habitat a to habitat b and $\mathbf{I}$ is the unit matrix. The diagonal terms, with a unit matrix $\mathbf{I}$, assure that the migration probabilities add to one.

The migration probabilities in the dispersal matrix change with time, depending on the timing of the migration. In cases where there is a single or are multiple dams obstructing the

migration route, the rates are decreased by the fish passage efficiency of the structure. In most cases, the migration success rate will differ whether the migration is upstream or downstream.

The demographic process for the spawning, feeding and refuge habitat is defined by three separate matrices:

$$\mathbf{A}^S = \begin{bmatrix} f_1 & f_2 & \dots & f_j & f_q \\ G_1 & P_2 & \dots & 0 & 0 \\ 0 & G_2 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & P_j & 0 \\ 0 & 0 & \dots & G_j & P_q \end{bmatrix} \quad \mathbf{A}^F = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ G_1 & P_2 & \dots & 0 & 0 \\ 0 & G_2 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & P_j & 0 \\ 0 & 0 & \dots & G_j & P_q \end{bmatrix} \quad \mathbf{A}^R = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ 0 & P_2 & \dots & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & P_j & 0 \\ 0 & 0 & \dots & 0 & P_q \end{bmatrix}$$

Each matrix contains habitat specific vital rates for each length class and is of dimension $q \times q$. P_j is the probability of surviving and staying in length class j , G_j is the probability of surviving and growing into the next length class, and, f_j is the average fecundity per fish for length-class j .

The above matrices represent different demographic process that may be occurring across the three habitats. With all the matrix elements of the first row set to zero this implies (i.e. $f = 0$ for all length classes) that the no reproduction occurs in these habitats and that growth probabilities, G , set to zero for the refuge habitat, models the effect of very low or no growth during the dry season.

The migration process from habitat a to b is defined by the following diagonal matrix:

$$\mathbf{M}_t^{ab} = \begin{bmatrix} m_1^{ab} & 0 & \dots & 0 & 0 \\ 0 & m_2^{ab} & \dots & 0 & 0 \\ 0 & 0 & \ddots & \vdots & \vdots \\ \vdots & \ddots & \ddots & m_j^{ab} & 0 \\ 0 & 0 & \dots & 0 & m_q^{ab} \end{bmatrix}$$

where $\mathbf{M}_t^{ab}$ is the probability that an individual of length class m_j^{ab} migrates from habitat a to habitat b at time t . In month t when there is no migration all the m_j^{ab} terms equal zero.

The migration sub-matrices $\mathbf{M}_t^{ab}$ permit the inclusion of complicated seasonal patterns of migration and the migration pattern of different length classes. For example, during the time of the spawning migration, mature fish can be set to migrate to the spawning habitat whereas the immature fish move to the feeding habitat as they leave the refuge habitat at the end of the dry season. This effect is achieved by setting the coefficients for the sub-matrices for $\mathbf{M}_t^{RS}$ and for $\mathbf{M}_t^{RF}$ to one for immature and mature class fish respectively at the time t of the migration.

The effect of passage obstruction of dams between habitat a and b on individuals in length class j is modelled by taking the product of the migration probability m_j^{ab} and the

proportion of individuals passing the obstruction successfully. Passage success rate may differ between upstream and downstream migration.

During the upstream migration from refuge to spawning habitat only mature fish attempt this migration while the juveniles migrate directly to the feeding habitat. At each dam crossing a certain proportion of individual pass the dam based on the passage efficiency (α) of the structure and the remaining migrate to the feeding habitat. For a single dam the proportion of adults that enter the spawning habitat is c and the remaining proportion $P_{RF} = (1-\alpha)$ return after encountering the obstruction to the feeding habitat. If there are two dams than the same fraction (α) migrate towards the second dam and the remaining migrate downstream through the dam. The individuals that survive the downstream migration migrate to the feeding habitat. In general for D number of dams the proportion of individuals from the refuge habitat that enter the spawning habitat is given by:

$$P_{RS} = \alpha^D$$

and the remaining proportion that enter the feeding habitat is given by:

$$P_{RF} = \sum_{i=0}^{D-1} (1-\alpha)(\alpha S_{turbine})^i$$

where $S_{turbine}$ is the survival rate through the turbine. The estimates for P_{RS} and P_{RF} are used in the sub-matrices $\mathbf{M}^{RS}$ and $\mathbf{M}^{RF}$, respectively.

In the downstream migration the proportion of individuals that successfully enter the feeding habitat when there are D dams is:

$$P_{SF} = S_{turbine}^D$$

this rate is used in the sub-matrix $\mathbf{M}^{SF}$.

Model parameter estimates

The transition probabilities in matrix $\mathbf{A}$, P_j and G_j can be calculated from estimates of the probability that an individual of length class j survives, σ_j , and that an individual of length stage j grows into the next length class, γ_j . Following the procedure based on Caswell (1989), G_j , the probability of surviving and growing to the next length stage is given by:

$$G_j = \sigma_j \gamma_j$$

and the probability of surviving, but not growing to the next length class is given by:

$$P_j = \sigma_j (1-\gamma_j).$$

The probability of survival, σ_j , can be expressed using an exponential mortality model:

$$\sigma_j = e^{-Z_j}$$

where Z_j is the total mortality and calculated by using the equation $Z_j = F_j + M_j$, where F_j is the rate of fishing mortality and M_j is the rate of natural mortality at length stage j .

Estimates for the duration of γ_j can be obtained from several approximation methods. According to Caswell (1989), the simplest approximation is $\gamma_j \approx \bar{T}_j^{-1}$, where $\bar{T}_j$ is the average duration that an individual will remain in length class j , based on a growth model. Other approximation methods are more complex in that either far more parameters or iterative equations are required (Caswell, 1989).

The fecundity term f_j is the expected number of offspring produced by a mature adult of stage length j . Individuals in stage lengths greater or equal to the length at maturity (l_m) only contribute to the recruitment process. Length at maturity is approximated using the following relationship (Beddington and Kirkwood, 2006):

$$l_m = 0.65L_\infty$$

where L_∞ is the asymptotic total length (cm).

Transition probability estimation

The transition probabilities, P_j and G_j can be expressed as functions of body length using a mortality-weight model developed by Lorenzen (1996). The natural mortality rates of fish are closely related to their body weight (*ibid*). The relationship between body weight and natural mortality is given by the following power function of weight $M_w = M_u W^c$ where M_w is the instantaneous annual natural mortality rate at weight $W(g)$, M_u is the mortality at unit weight, and c is the allometric scaling factor. Based on empirical studies, Lorenzen (1996) estimates the exponent (c) and mortality at unit weight for fish in six ecosystems within a selected population, species and families. For river systems, mortality-weight model parameter estimates for river systems were determined as $b = -0.289$ [90% C.I., -0.360, -0.230] and $M_u = [90\% \text{ C.I., } 2.29, 2.96]$. Using the allometric relationship between weight and body length:

$$W = aL^b$$

and substituting into the mortality-weight model, the natural mortality rate can be expressed as a function of body length (L , cm):

$$M_L = M_u (aL^b)^c = M_u a^c L^{bc}$$

For an unexploited stock, the monthly survival rate, S , as expressed as function of body length is:

$$S(L) = e^{-M_a a^c L^{bc} / 12}$$

The average survival rate for a given length class, with individuals ranging in length over the interval from l_1 to l_2 , is:

$$\bar{S} = \frac{1}{l_2 - l_1} \int_{l_1}^{l_2} e^{-M_a a^c L^{bc} / 12} dl \approx \frac{1}{2} (S(l_2) + S(l_1))$$

The above integral can be approximated numerically using the trapezoid rule (Press *et al.*, 1994) and the survival rate of length class j , containing individuals over the length interval l_1 to l_2 , is:

$$\sigma_j \approx \frac{1}{2} (S(l_2) + S(l_1))$$

In other words, for an unexploited population (i.e. $F=0$) the survival rate is approximately equal to the average value of the instantaneous survival rate at l_1 and l_2 as a first order approximation.

The duration of each length class j is determined from the Ludwig von Bertalanffy (LVB) growth model:

$$l(t) = L_{\infty} (1 - e^{-Kt})$$

where $l(t)$ is the length at time t and the parameters L_{∞} and K , are the asymptotic length (cm) and the growth parameter (1/year), respectively. Estimates of K corresponding to L_{∞} were derived from $K = 3.3492 L_{\infty}^{-0.6673}$ (Lorenzen *et al.*, 2006).

Estimates of L_{∞} for each model species were obtained from the literature or assumed to be approximately equal to the $L_{\max}$ (maximum reported fish length) quoted in the MFD or FishBase. The coefficient and exponent of weight-length relationships for each model species were estimated from regressions of loge-transformed length and weight observations for individual fish from the AMCF survey (see Annex 5 and Table 2.7).

Table 2.7 Weight-length relationships based on data collected under the AMCF survey (2003–2005).

Species	intercept	exponent	R ²
	<i>a</i> (SE)	<i>b</i> (SE)	
<i>Botia helodes</i>	0.0074 (0.29)	3.24 (0.11)	0.89
<i>Cosmochilus harmandi</i>	0.0233 (0.08)	2.94 (0.02)	0.91
<i>Cynoglossus microlepis</i>	0.0378 (0.40)	2.39 (0.13)	0.66
<i>Gyrinocheilus pennocki</i>	0.0155 (0.30)	2.95 (0.10)	0.90
<i>Henicorhynchus lobatus</i>	0.0108 (0.43)	3.14 (0.17)	0.79
<i>Henicorhynchus siamensis</i>	0.0297 (0.28)	2.80 (0.11)	0.74
<i>Hypsibarbus malcolmi</i>	0.0268 (0.11)	2.91 (0.04)	0.92
<i>Macrobrachium</i> sp.	0.0651 (0.50)	2.63 (0.19)	0.91
<i>Pangasianodon gigas</i>	0.0263 (1.09)	2.71 (0.36)	0.97
<i>Pangasius conchophilus</i>	0.0209 (0.12)	2.86 (0.03)	0.84
<i>Paralauca typus</i>	0.0531 (0.29)	2.36 (0.12)	0.66
<i>Probarbus jullieni</i>	0.0070 (0.14)	3.32 (0.05)	0.92

Note: The weight-length relationship is in the form, $W = a L^b$ where W is in grams and L in cm. R²—coefficient of determination for the weight-length regression model. The scatter plots with fitted regression models are shown in Appendix 5.

The LVB model can be recast to determine the time to reach a certain body length l :

$$t_l = -\frac{1}{K} \ln \left[\frac{L_\infty - l}{L_\infty} \right]$$

For a growth increment from length l to $l + \Delta l$ the time duration is simply $\Delta t = t_{l+\Delta l} - t_l$. For a given species as specified by L_∞ , it is possible to parameterise the VBGF growth model and to calculate the time duration to grow a fixed length increment. If the average duration of length stage j , made-up of individuals from length l to Δl is Δt , then during each time interval a fraction $1/\Delta t$ of the individuals must grow to the next stage,

$$\gamma_j \approx 1/\bar{T}_j = 1/\Delta t$$

Thus the estimates of survival and stage duration can be obtained as a function of L_∞ .

Building the transition matrix requires specifying the number and width of each length class. Here, the width and number of length classes for each species is selected so as to have representative length classes for both immature and mature size fish. The width of the first length class is determined by the size of the larvae after 15 days of growth using the von Bertalanffy growth function. The width of the last length class is set to be from 95% of L_∞ to L_∞ . For the remaining length, between the first and last length classes, the width of the class is set by the user. For fish smaller than 120 cm the class width ranges from 5–10 cm and for fish greater than 120 cm, it ranged from 30–45 cm. Based on this length discretisation method, growth transition of all possible age of fish is maintained. Overall the number of length classes varied from 5–12, with larger fish species generally having more number of length classes.

Fecundity estimation

Few estimates of fecundity as a function of body size were found for the model species in the literature. Consequently, we employed a method of back calculation to determine the equivalent fecundity values of mature length class fish for a given intrinsic population growth rate r . Values of r for each species were estimated from population doubling time quoted FishBase (<http://www.fishbase.org>).

The doubling time is related to intrinsic population growth, r_d by:

$$r_d = \log(2)/t_d$$

and consequently λ by:

$$\lambda = e^{r_d} = e^{\log(2)/t_d}$$

The dominant eigenvalue of the matrix **B** provides a measure of the population growth λ . Consequently, it is possible to calibrate the fecundity value, f_i for the mature stage classes, such that the dominant eigenvalue of the matrix is equal to the intrinsic population growth rate, r_d , or to λ .

The doubling time of species quoted in FishBase is estimated using a variety of methods and data sources, including spawner-recruitment or length-frequency data. In data-poor situations it is estimated based on generation time, age at maturity, natural mortality estimates, growth rate estimates and various fish length characteristics (e.g. asymptotic length and length at maximum egg production). No one method or single data set covers the modelled species for this study. Thus the doubling time for the modelled species may be derived using one or more methods of estimate or from different data sets. No doubling time estimates were available for *C. microlepis*. This species together with *M. rosenbergii* were therefore not included in the model simulations.

In applying the back-calculation method we estimated the fecundity values corresponding to three different intrinsic population growth rate values, ranging in value from $\lambda = 1.64$ to $\lambda = 1.04$ depending on the fish species, equivalent to annual percentage growth rates of 64% and 4%, respectively. The first two values are based on the range of the maximum intrinsic growth rate reported in Fish Base and the third value corresponds to low growth rate. The intrinsic rate of growth for any population can be influenced by various extrinsic factors. For the modelled species, the intrinsic population growth rate may vary annually in response to changes in hydrological conditions, dry and flood season areas and volumes, and flood season duration, for example. Thus by selecting three different values we hope to account for both the uncertainty in the reproductive potential of the populations and any environmental effects.

Population Projection

The time step in the above model is monthly, which allows us to capture the duration that individuals stay in each of the habitat types and the migration process between habitats. To model the dynamics at an annual time scale, the above model can be written equivalently as:

$$\begin{aligned}\mathbf{n}_{t+12} &= \mathbf{A}_{12}\mathbf{A}_{11}\mathbf{A}_{10}\cdots\mathbf{A}_2\mathbf{A}_1\mathbf{n}_t \\ &= \mathbf{B}\mathbf{n}_t\end{aligned}$$

where the matrix $\mathbf{B} = \prod_{j=1}^{12} \mathbf{A}_j$ describes the population growth over a single year. The dynamics of the population at an annual time scale are described by the eigenvalues and eigenvectors of $\mathbf{B}$ (Caswell, 1989). The matrix captures $\mathbf{B}$ the periodic dynamics of migration and periodic variation in the vital rates as individuals inhabit different habitat types throughout the year. The dominant eigenvalue of matrix $\mathbf{B}$ gives the asymptotic annual growth rate of the population (λ).

The natural logarithm of λ ($\ln(\lambda)=r$) is the intrinsic rate of population change. The right and left eigenvectors $\mathbf{B}$ represent the stable age distribution and the reproductive values for each age class respectively (Caswell, 1989).

Population number and number of individuals per length-class at an annual time step are given by the following recursion equation:

$$\mathbf{n}_{t+1} = \mathbf{B}\mathbf{n}_t$$

The population growth rate and stable length-class distribution can be calculated by deterministic projections or by matrix computations using the dominant eigenvalue and right eigenvector (Caswell, 1989). In the first case, the above equation is used repeatedly to create a time series of stage vectors. Eventually, the stage vector $\mathbf{n}_t$ converges to a stable length-class distribution, where number of individuals in each length-class changes by the same proportion (λ) with each progressive iteration. The second method requires using computer-based numerical methods to calculate the dominant eigenvalue of matrix $\mathbf{B}$, and the eigenvectors (Press, 1994; Insightful, 2007). We used the built-in function *eigen* in S-PLUS to calculate the eigenvalues and eigenvectors of the projection matrix.

The value of λ provides valuable information about the status of the population. Estimates of λ for different scenarios may highlight conditions if the population can be harvested ($\lambda > 1$), viable ($\lambda \approx 1$) and under risk ($\lambda < 1$). With the above model it is possible to build species-specific population model, with specific survival rate for different species and migration timing among the habitats. It is also possible to explore the impact of dams by modifying survival probabilities of different migratory corridors.

Modelling intra-annual behaviour of populations

Within year population dynamics is modelled using the equation $N_{t+1} = A_t N_t$ where the transition matrix A_t projects the population forward from month t to month $(t+1)$. The length specific vital rates were parameterized by means of the growth and mortality sub-models. Using an iterative process, the fecundity rate was determined so that the population growth rate matched the reproductive potential for the species (Table 2.8 on page 43).

Modelling passage rates for a single dam

Operation practices and design characteristics of a dam can potentially impact the upstream and downstream passage success rate. The impact of these rates on annual population growth rate is determined using the following model: $N_{t+1} = B_t N_t$ where B is the product of all the monthly matrices ($A_{12} \dots A_1$). This formulation allows the retention of temporal changes in the parameters and allows us to estimate the annual population growth rate λ , which is equal to the dominant eigenvalue of B .

Using contour plots and tabular summaries, we examined the effects of combinations of upstream passage success and downstream survival rates on the population growth rate λ . Viable populations were defined as those with λ values greater than or equal to one under baseline conditions of high, medium and low reproductive potential. The upstream passage success rate refers to the proportion of adults that successfully migrate upstream through a single dam whereas the downstream passage refers to the proportion of mature fish that safely by-pass the turbine. In these set of simulations, it is assumed that all juveniles pass through the turbines. The sensitivity of the model predictions to this assumption is examined in Chapter 3 and Chapter 4.

Model parameter summary

The model parameter summary for the ten species for which parameter estimates were available is given in Table 2.8 on page 43. For the small species, rates of exploitation described by the annual instantaneous fishing mortality rate, F were set to the lowest estimate ($F=0.5$) for 22 species exploited in Ubolratana reservoir, Thailand reported by Moreau *et al.* (2008). This is equivalent to catching 40% of the population each year. We chose to use the lowest estimate reported by these workers because fish inhabiting reservoirs are likely to be more vulnerable to capture than those in riverine environments. For the remaining large species, we set $F=0.1$ (approximately 10% of the population caught each year) corresponding to the estimate for *P. gigas* reported by Lorenzen *et al.* (2006). Except for *P. gigas*, these estimates of F are a significant source of uncertainty in the model. We therefore recommend that model predictions with and without fishing mortality are carefully compared. Species were categorized as either 'small' or 'large' if their estimated length was less than or greater than 50 cm, respectively.

Table 2.8 *Model parameter estimates.*

Species	Size category	L_{∞} (cm)	L_m (cm)	F (y^{-1})	W-L model		K (y^{-1})	$\lambda_{baseline}$		
					a	b		λ_{low}	λ_{med}	λ_{high}
<i>Henicorhynchus lobatus</i>	Small	15	9.8	0.5	0.012	3.026	0.550	1.07	1.19	1.64
<i>Henicorhynchus siamensis</i>	Small	20	13	0.5	0.030	2.8	0.454	1.11	1.19	1.65
<i>Paralauca typus</i>	Small	20.5	13.3	0.5	0.053	2.357	0.446	1.09	1.27	1.67
<i>Gyrinocheilus pennocki</i>	Small	28	18.2	0.5	0.017	2.92	0.363	1.14	1.41	1.66
<i>Botia helodes</i>	Small	30	19.5	0.5	0.007	3.254	0.346	1.10	1.16	1.62
<i>Hypsibarbus malcolmi</i>	Large	50	32.5	0.1	0.027	2.909	0.246	1.05	1.10	1.18
<i>Cosmochilus harmandi</i>	Large	100	65	0.1	0.023	2.94	0.155	1.04	1.06	1.17
<i>Pangasius conchophilus</i>	Large	120	78	0.1	0.021	2.86	0.137	1.02	1.05	1.17
<i>Probarbus jullieni</i>	Large	150	97.5	0.1	0.016	3.0	0.118	1.02	1.03	1.05
<i>Pangasianodon gigas</i>	Large	290	188.5	0.1	0.040	2.8	0.150	1.03	1.07	1.15

Note: It is assumed that L_{∞} approximates the maximum reported length L_{max} reported in FishBase; length at maturity (L_m) and K are estimated using allometric relationships (see text); values for the λ s are derived from population doubling time as reported in FishBase and values of a and b are the regression coefficients for the weight-length relationships (see Table 2.7 on page 39).

2.6 Summary of the main model assumptions

The main assumptions underlying the study are summarized in Table 2.9 below.

Table 2.9 *The main assumptions underlying the modelling study.*

Subject	Assumptions	Comments and Recommendations
Proportion of catch in the LMB identified as vulnerable.	MRC catch assessment survey (CAS) provides a representative sample of total landings by species in the LMB.	- Unlikely to be valid given that the CAS mostly targeted gillnet fishers operating in the mainstream but no better alternatives. - More reliable estimates would require a basin-wide and species-wise household or fisher-based catch assessment survey with appropriate stratification to account for temporal, spatial and habitat-dependent variation in fish catches.
Longitudinal distribution of critical habitat.	- All spawning habitat is located upstream (above) of the uppermost dam, and - All feeding and nursery habitat is located downstream of (below) the lowermost dam.	- Sensitivity of results to these assumption not examined, but likely to be high. - Undertake a sensitivity analysis for a range of alternative assumptions concerning spawning habitat distribution (e.g. normal, uniform, skewed...etc) and/or incorporate empirical model of distribution based upon larvae surveys.
Population structure.	Species assumed to comprise a single population in the LMB.	- Sensitivity of results to this assumption not examined, but likely to be high. - More DNA studies required.

Subject	Assumptions	Comments and Recommendations
Upstream passage of adults to spawning grounds.	• No mortality or diminished reproductive capacity associated with upstream passage via ladders or other passes.	• Some mortality and diminished reproductive capacity expected due to high energetic costs associated with passage and increased likelihood of predation in dam vicinity. Results therefore likely to be conservative.
Downstream passage of juveniles.	• All juvenile fish pass downstream through dam turbines.	• Juvenile fish have limited capacity to avoid entrainment (swimming capacity is a function of fish length). Limited ability to screen turbines without compromising turbine efficiency. Results insensitive to this assumption (see Section 3).
Downstream passage of adults and juveniles via spillways or by-passes	• Mortality rates are zero for these passage routes.	• Some mortality is likely so results may be conservative.
Downstream passage of adults and juveniles via turbines.	• Mortality rates can be accurately predicted by the turbine geometry and rotation speed selected.	• Mortality rates of medium size fish may be overestimated if turbine rotation speeds are lower than those selected but this is unlikely to affect the study conclusions given the other assumptions concerning fish passage. Re-run model when actual turbine rotation speeds and geometry are known.

3. Results

3.1 Downstream mortality

Turbine blade strike model

Based on engineering parameters for a Kaplan turbine operating at maximum efficiency (Ferguson *et al.*, 2008, Table 2), the probability of a blade strike and associated mortality for different fish species is shown in Figure 3.1 on page 47. Larger individuals of a given species are more likely to be struck by a turbine blade than smaller individuals. Across species, this probability increases for larger species. For example, the probability of a blade strike event for *Henicorhynchus lobatus* (15 cm) is approximately 25% whereas for *Cosmochilus harmandi* (100 cm) it is approximately 100%.

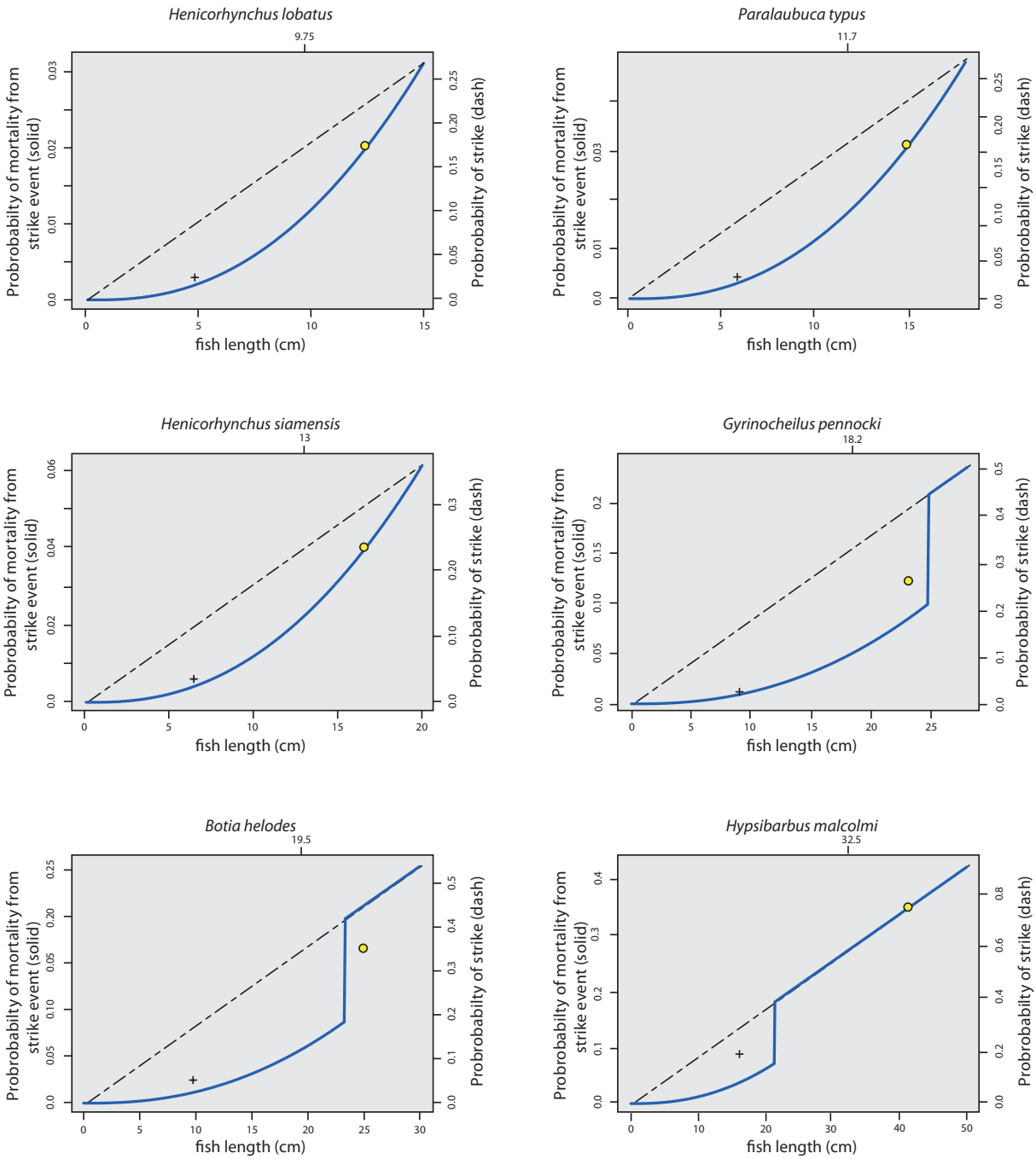
Probability of mortality is the product of the odds of being struck by a blade and the mutilation ratio. The discontinuity in the relationship between mortality rate and body length is due to the nature of how the mutilation ratio changes with body length (see Chapter 2). For species greater than 150 cm the adult mortality rate is near one. In general, the mortality of juveniles of a given species is less than that of adults. For small fish species the difference between the mortality rate of average-size juveniles and adults is slight but for larger species the difference is considerable (Figure 3.1 on page 47). The model results show the probability of a blade contact resulting in mortality increase with body length, with mature size fish at greater risk than juveniles

Using a similar model, Ferguson *et al.* (2008) reported that the mean blade strike mortality was higher for adult salmon (*Salmo salar*) and brown trout (*Salmo trutta*) (25.2–45.3%) than for juveniles (5.3–9.7%). Experimental work based on released fish of average length of 16.5 cm showed an average predicted blade-strike injury range of 3.1 to 4.3% (Deng *et al.*, 2005, Table 4.3 and 4.4.). As a comparison, for a same length fish the model predicts a value of 2.5%. Our model predictions are therefore consistent with those of other workers.

3.2 Predicted population response

Intra-annual behaviour of populations without dam barriers and exploitation

The seasonal and temporal dynamics of the model are illustrated with example to *H. malcolmi* (Figure 3.3 on page 48) which shows the distribution and the abundance of each length-class through time. The model can be seen to effectively capture the migration between habitats.



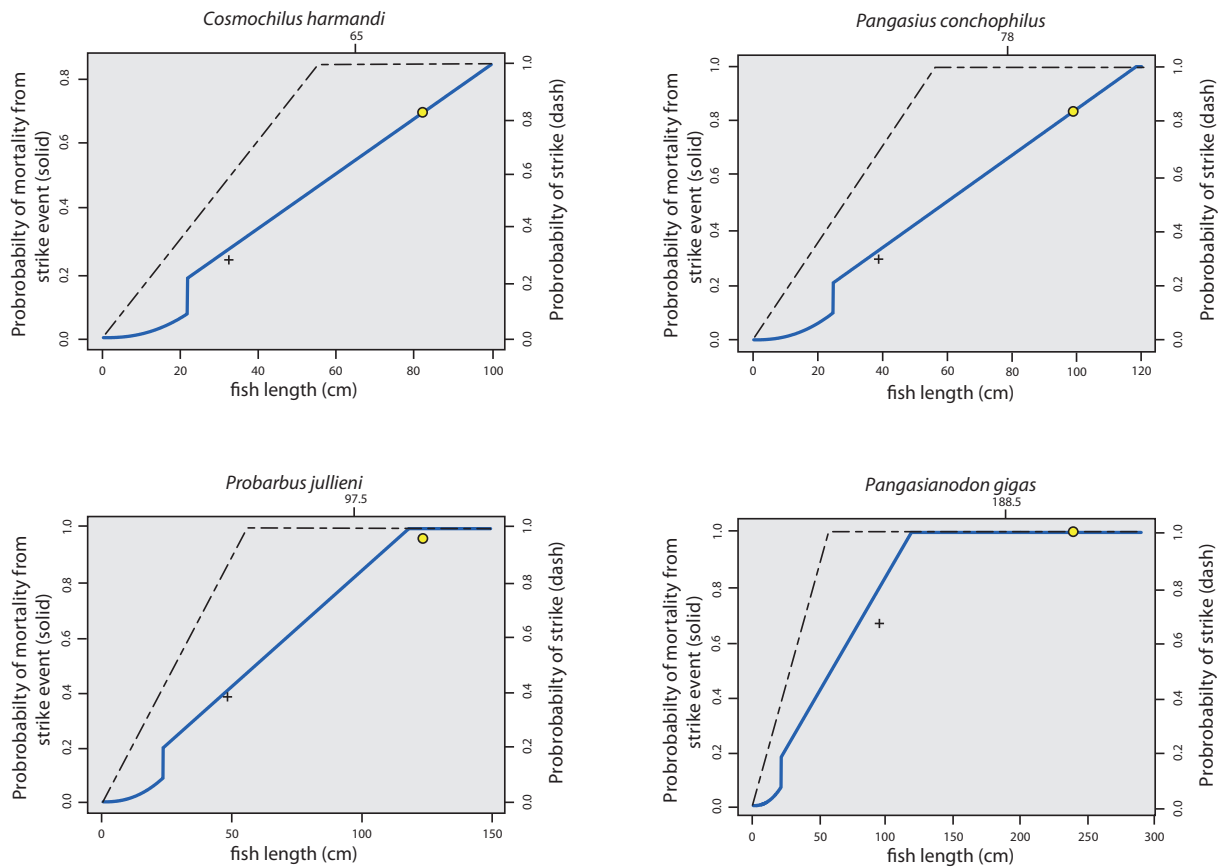


Figure 3.1 Probability of mortality from blade-strike event (left axis, solid line) and of blade-strike (right axis, dash line) based on a turbine blade-strike model. The input parameters for a Kaplan turbine are given in Ferguson *et al.* (2008). The value on the upper axis is the length at maturity. Mean probability of mortality from a strike-event for juvenile and mature fish is indicated by the '+' and '0' symbol respectively.

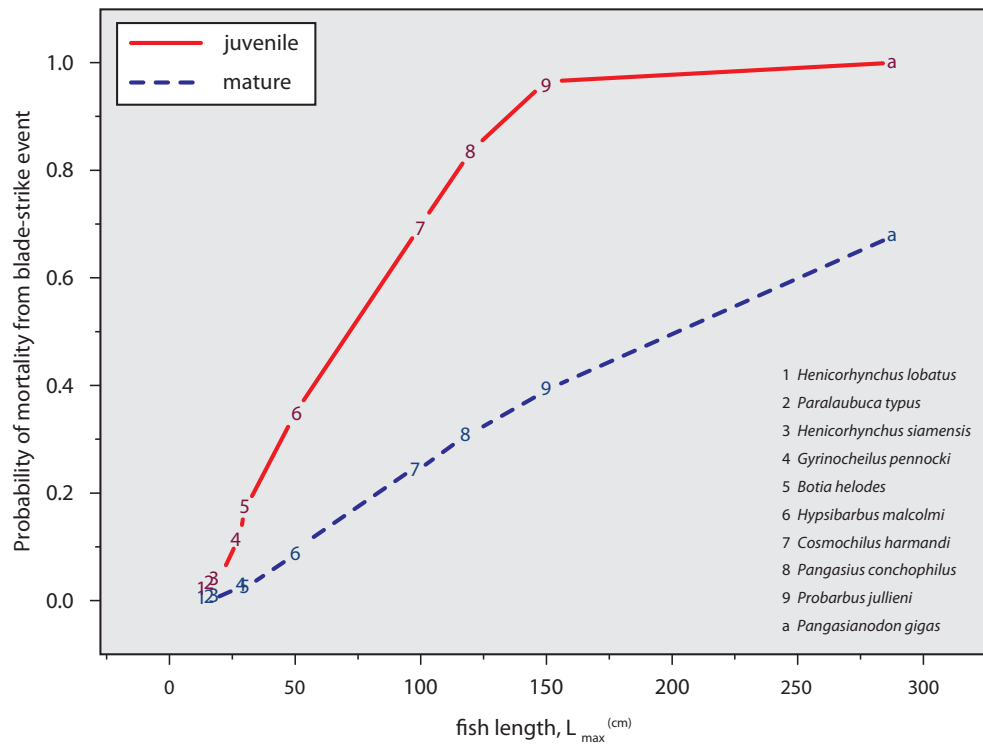


Figure 3.2 Predicted mortality probability based on the turbine blade-strike model for juvenile and mature class individuals for different species.

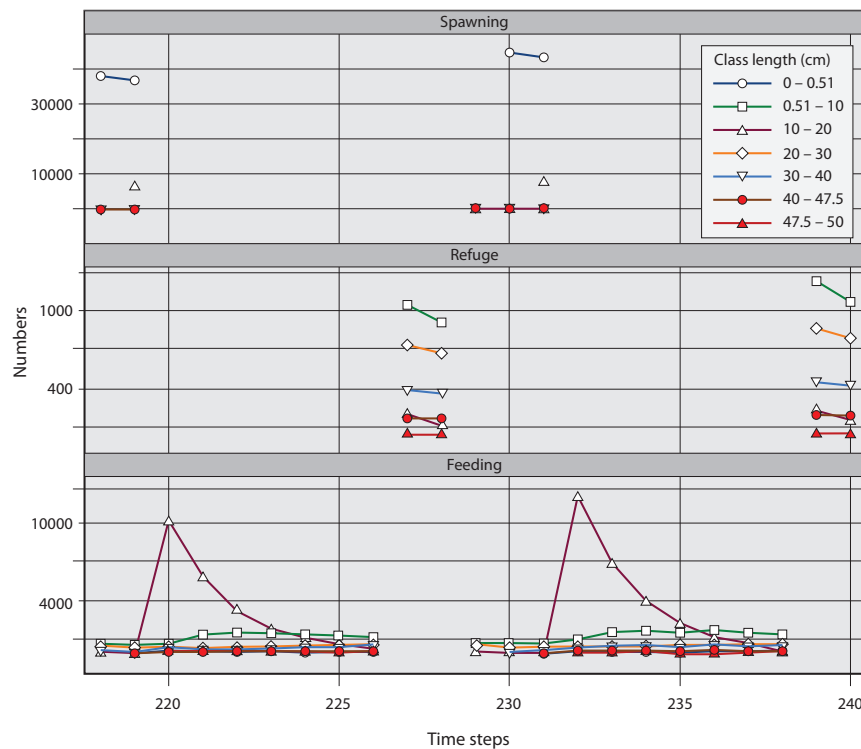


Figure 3.3 Based on numerical simulation, the spatial and temporal dynamics of *H. malcolmi* across the three habitat types over a 23 month period for different length-classes and a baseline scenario corresponding to a high lambda (1.17). A unit increment of the x-axis is one month in duration

All length classes except the larvae stage (0–0.51 cm) are found in the refuge habitat during the dry season (middle panel, Figure 3.3). The model output shows that at the end of the dry season, mature fish (40+ cm) migrate to the spawning habitat and the remaining immature fish to the feeding habitat. In spawning habitat, larvae appear and grow into the next length class (0.51–10 cm, open triangle). This length class migrates with the mature size fish to the feeding habitat. When the feeding migration is complete, all the length class with the exception of larvae are in the feeding habitat. In the feeding habitat, the population composition changes with mature fish being more relatively abundant. The model therefore mimics well the spatial shift in distribution that is typical of freshwater migratory fish.

The model results show a marked fluctuation in abundance of individuals of different length classes (Figure 3.4). This inter-annual variation is due to a migration pattern and not any environmental factors such as temperature or hydrological processes, which are assumed to be constant. In the model the vital rates change as individuals leave one habitat and enter another habitat. Effectively, the population experiences living in a periodically fluctuating environment by migrating between habitats. As a consequence, the composition of the population changes throughout the year. The model result shows that larvae and post-larvae classes can make up a high proportion of the population in terms of absolute numbers (Figure 3.4). During the middle of the year juvenile and mature individuals (>10 cm) are more dominant and start to decrease during the onset of the dry season.

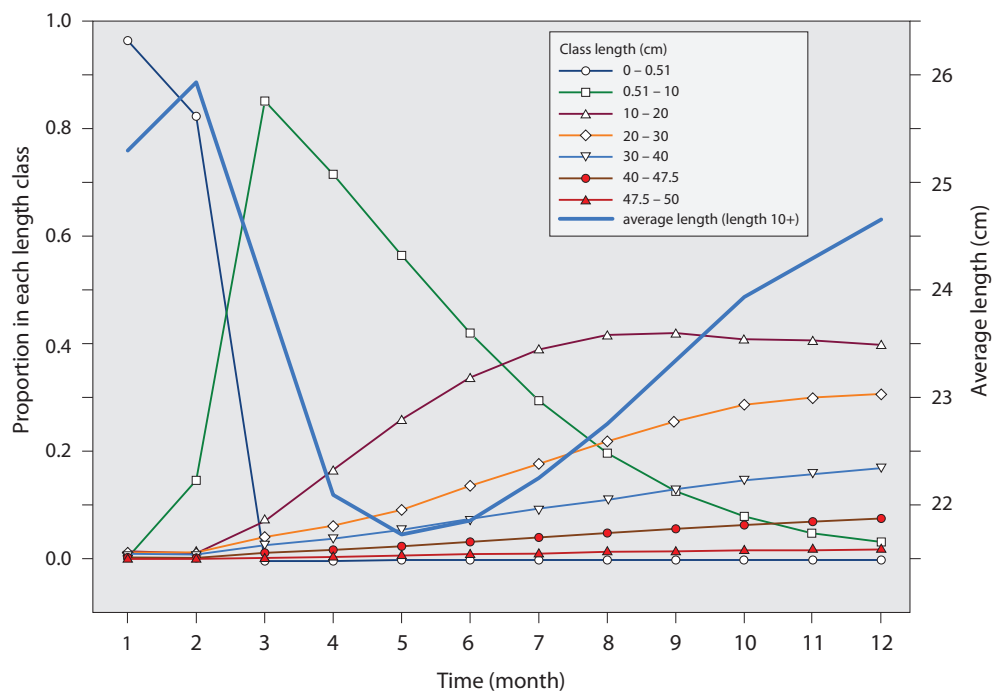


Figure 3.4 Changes in population composition by length class over an annual cycle. In the first two or three months, larvae and post-larvae class make up a high proportion of the population in terms of absolute numbers. During the middle of the year juvenile and mature individuals (10+ cm) become more dominant and start to decrease during onset of the dry season, when migration to refuge habitat occurs. The grey solid line is the average length of individuals that are larger than 10 cm.

These model predictions are consistent with observations of seasonal changes in fish abundance and mean weight (length) made under the AMCF catch monitoring programme (Figure 33). Observed declines in mean fish weight/length begin in January corresponding to the model month 2 in Figure 18. Since we are primarily interested in inter-annual long term changes in population size and have not considered seasonal flow or dam operation effects in this set of simulations, model month is an arbitrary term and need not correspond to the numerical calendar month allowing different life-cycles to be described by the model. Average fish length is predicted to decrease towards the middle of the model year due to the dilution effect of large number of juveniles appearing in the population. Average fish length then begins to increase as juveniles grow into adults. By the end of the model year, the population consists of large fish and thus the average population length increases. These seasonal changes in average fish size are typical of the other modelled species (see Appendix 2).

Passage rates for a single dam without exploitation (fishing)

As expected, low upstream passage success and high downstream mortality rates (low percentage of adult fish avoiding turbine passage) reduce population growth rates described by λ (Figure 3.5–Figure 3.9 and Tables 13–17 in Appendix 6).

Under some combinations, populations of some species are unable to persist because $\lambda > 1$. Minimum upstream passage success and downstream survival rates to maintain viable populations increase with declining reproductive potential (top to bottom panel in each figure). The region where $\lambda < 1$ becomes larger with increasing species size.

Small species

For small species and assuming high reproductive potential, minimum upstream passage success to maintain viable populations varied from 40% to 60% assuming that all mature fish can be safely re-directed away from turbines when returning downstream. This represents the most conservative scenario.

Under the low reproductive potential assumption, minimum upstream passage success to maintain viable populations climbs to 80% - 90% still assuming that all mature fish can be safely re-directed away from turbines when returning downstream (Figure 3.5–Figure 3.7 and Table A6.1–Table A6.5 in Appendix 6).

If minimum upstream passage success rates of 60% could be achieved, then the proportion of mature fish that would need to be safely re-directed away from turbines when returning downstream would need to exceed 80% to maintain viable populations of all five small species.

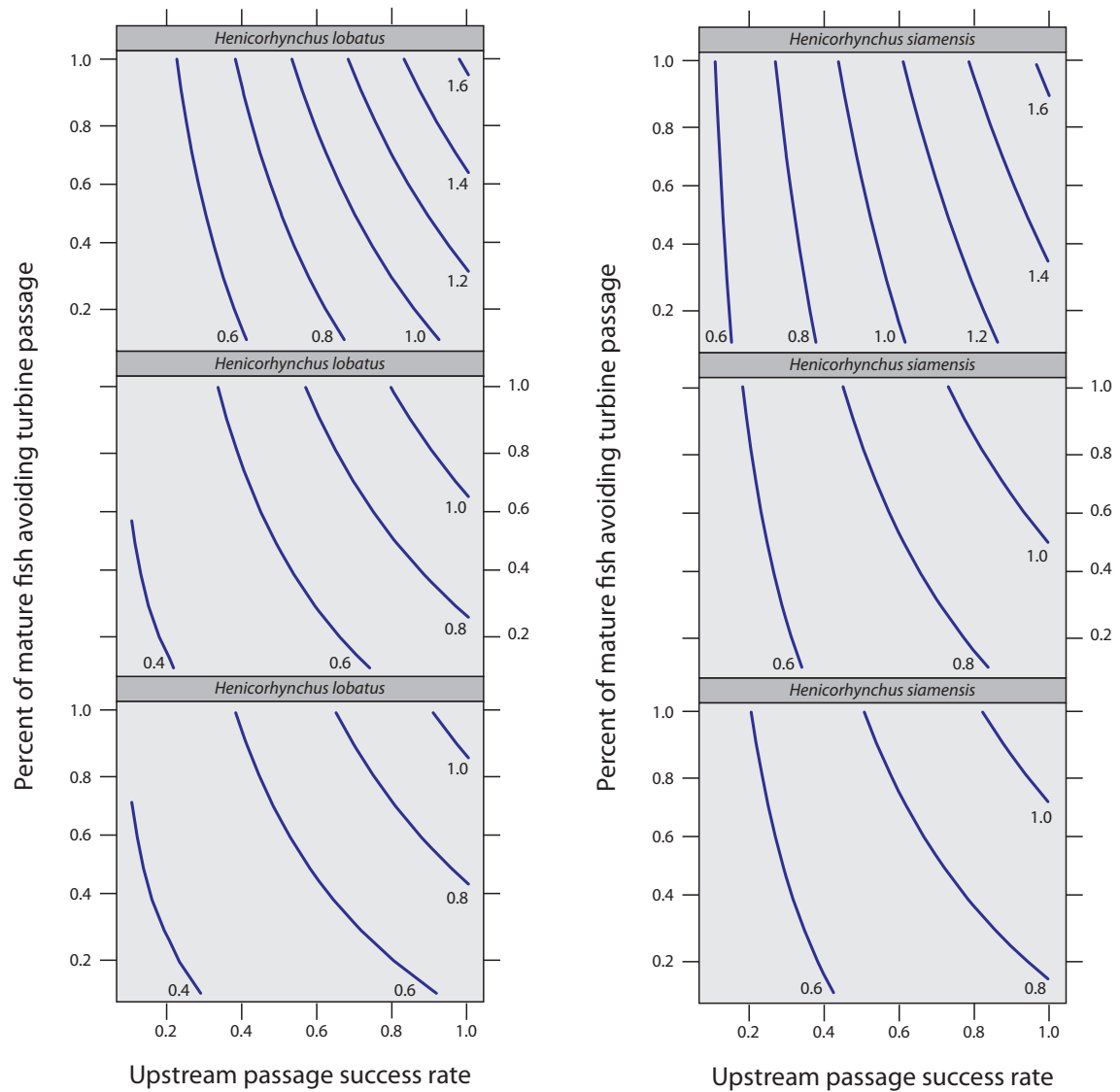


Figure 3.5 Contour plots of λ for *Henicorhynchus lobatus* and *Henicorhynchus siamensis* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation. Figures are arranged from top to bottom in descending order of reproductive potential (high, medium and low).

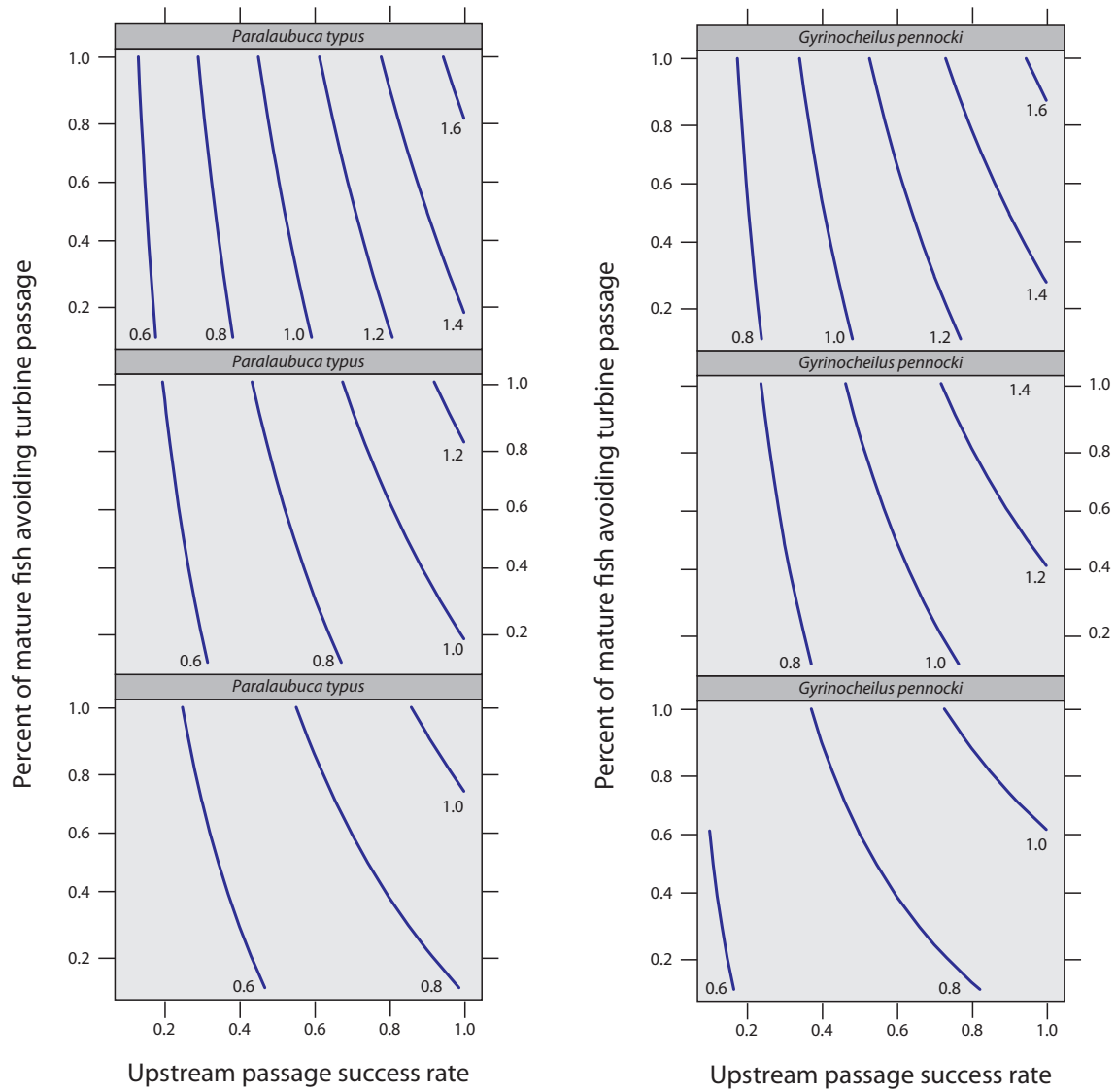


Figure 3.6 Contour plots of λ for *Paralabuca typus* and *Gyrinocheilus pennocki* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation. Figures are arranged from top to bottom in descending order of reproductive potential (high, medium and low).

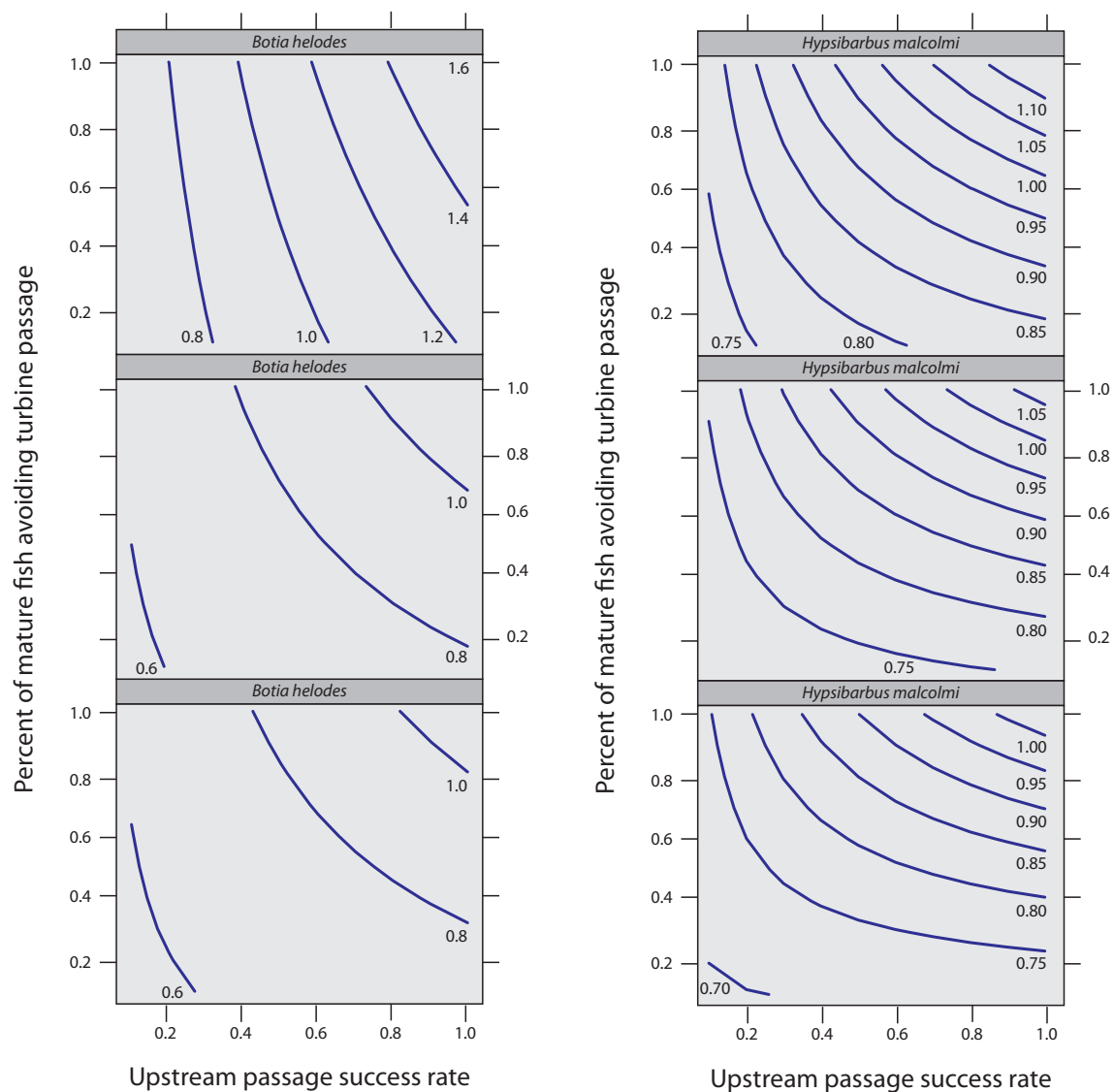


Figure 3.7 Contour plots of λ for *Botia helodes* and *Hypsibarbus malcolmi* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation. Figures are arranged from top to bottom in descending order of reproductive potential (high, medium and low).

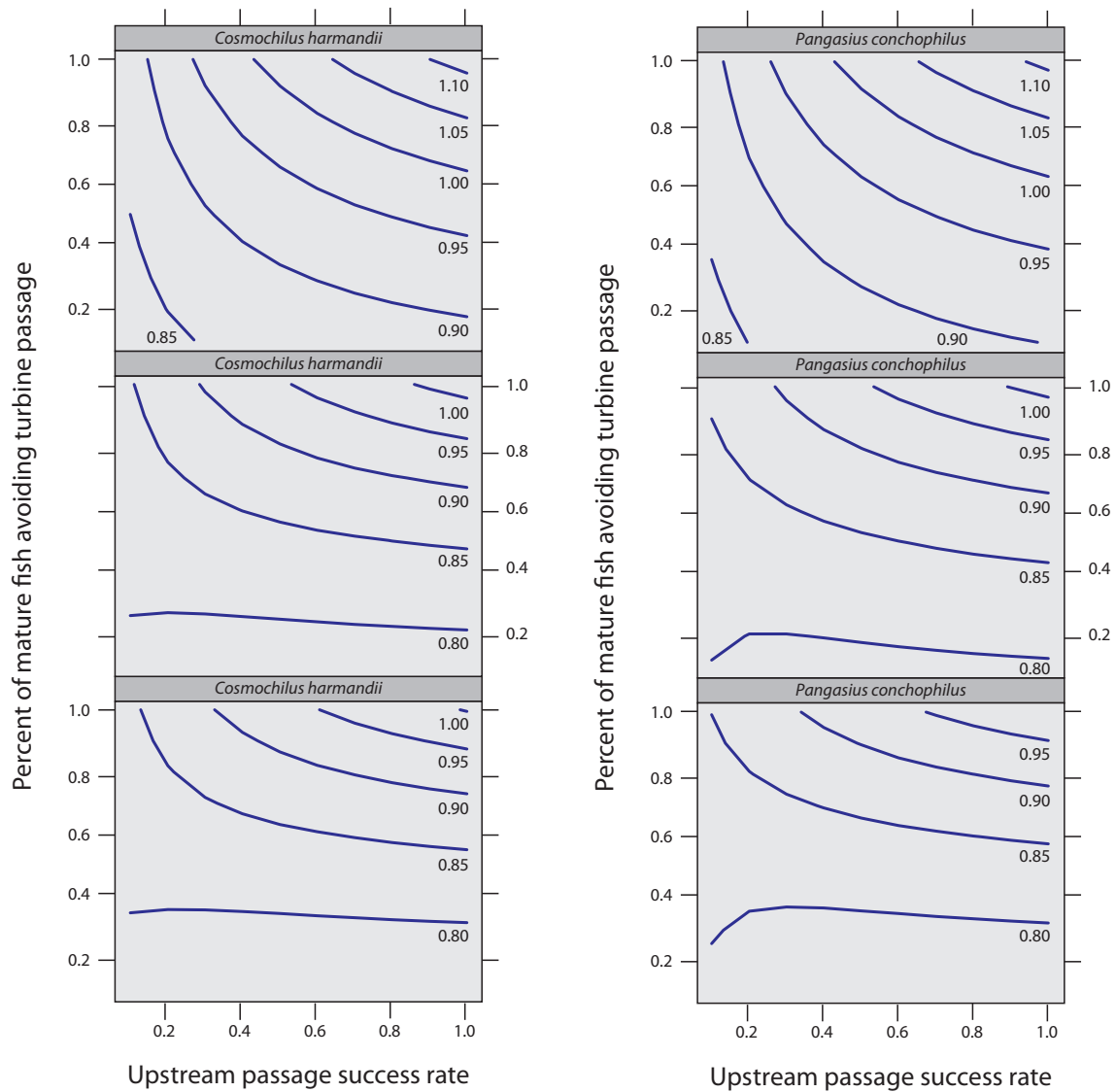


Figure 3.8 Contour plots of λ for *Cosmochilus harmandii* and *Pangasius conchophilus* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation. Figures are arranged from top to bottom in descending order of reproductive potential (high, medium and low).

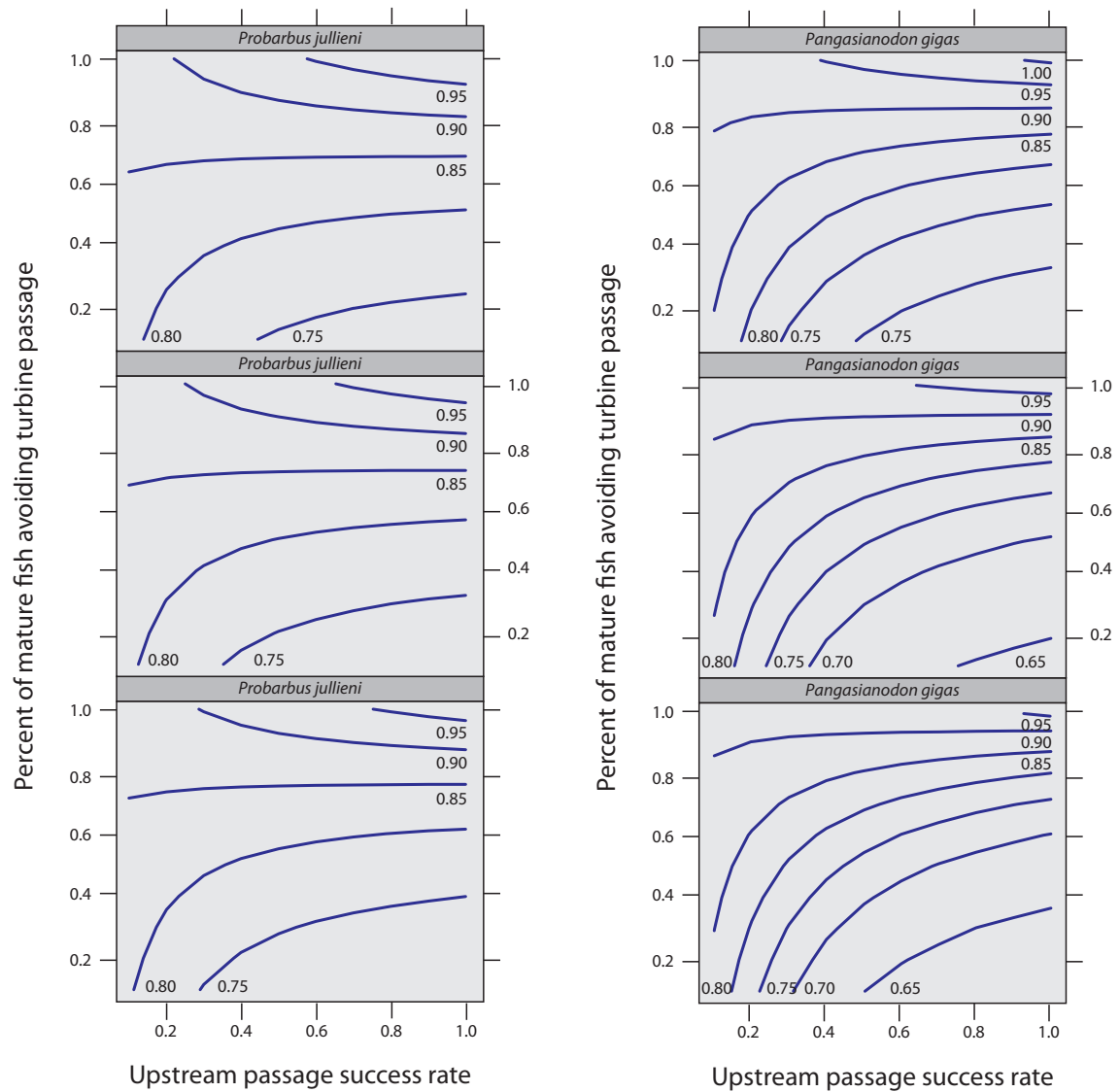


Figure 3.9 Contour plots of λ for *Probarbus jullieni* and *Pangasianodon gigas* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation. Figures are arranged from top to bottom in descending order of reproductive potential (high, medium and low).

Large species

Large species are much less resilient to dam passage effects. Under the most conservative assumptions of high reproductive potential and no adult downstream passage via dam turbines, minimum upstream passage success to maintain viable populations varied from 50% - 90% assuming that all mature fish can be safely re-directed away from turbines when returning downstream. Populations of *Probarbus jullieni* were predicted not to be viable under these most conservative assumptions even if upstream passage success rates were 100% and if all returning adults could be safely re-directed away from turbines. Elevated mortality rates on juvenile fish as they return downstream through the turbines exceed the intrinsic population growth rate of this species.

Under the low reproductive potential assumption, but still assuming that all mature fish can be safely re-directed away from turbines, populations of only two of the five species (*H. malcolmi* and *C. harmandii*) belonging to our large fish category would remain viable (Figure 3.8–Figure 3.9 and Table A6.3–Table A6.5 in Appendix 6).

Cumulative dam effects with and without exploitation (fishing)

Minimum upstream passage success to maintain viable populations ($\lambda = 1$) of fish that are obliged to cross more than one dam to complete their life-cycles are examined in Figure 3.10 to Figure 3.13. The symbols in each plot refer to the three assumptions about the proportion of adults passing downstream through dam turbines ranging from 25% to 100%. A cross beside the species name indicates that the population is not viable under any rates of upstream passage success. In other words, the modelled downstream mortality rates of adults and juveniles exceed the population's rates of reproduction even if all adult fish were able to successfully migrate upstream.

Under less favourable reproductive potential conditions, the minimum passage requirement dramatically increases for all species (compare Figure 3.10 and Figure 3.12). Not surprisingly, the highest passage rate requirement occurs under conditions where the reproductive potential is the lowest and the when three dams must be passed (Figure 3.12, upper panel).

Small species – no exploitation

Under the most conservative assumptions of no exploitation and high reproductive potential ($\lambda_{\text{baselinf}} = \lambda_{\text{high}}$) minimum upstream passage success rates to maintain viable populations are in excess of 0.35 or 35% for a single dam, increasing to approximately 70%–80% for three dams assuming that 25% of adult fish pass downstream via the dam turbines (Figure 3.10). When reproductive potential is assumed to be low, minimum upstream passage success climbs to at least 75% for a single dam to more than 90% for three dams, still assuming that only 25% of returning adult fish pass downstream via dam turbines (Figure 3.12).

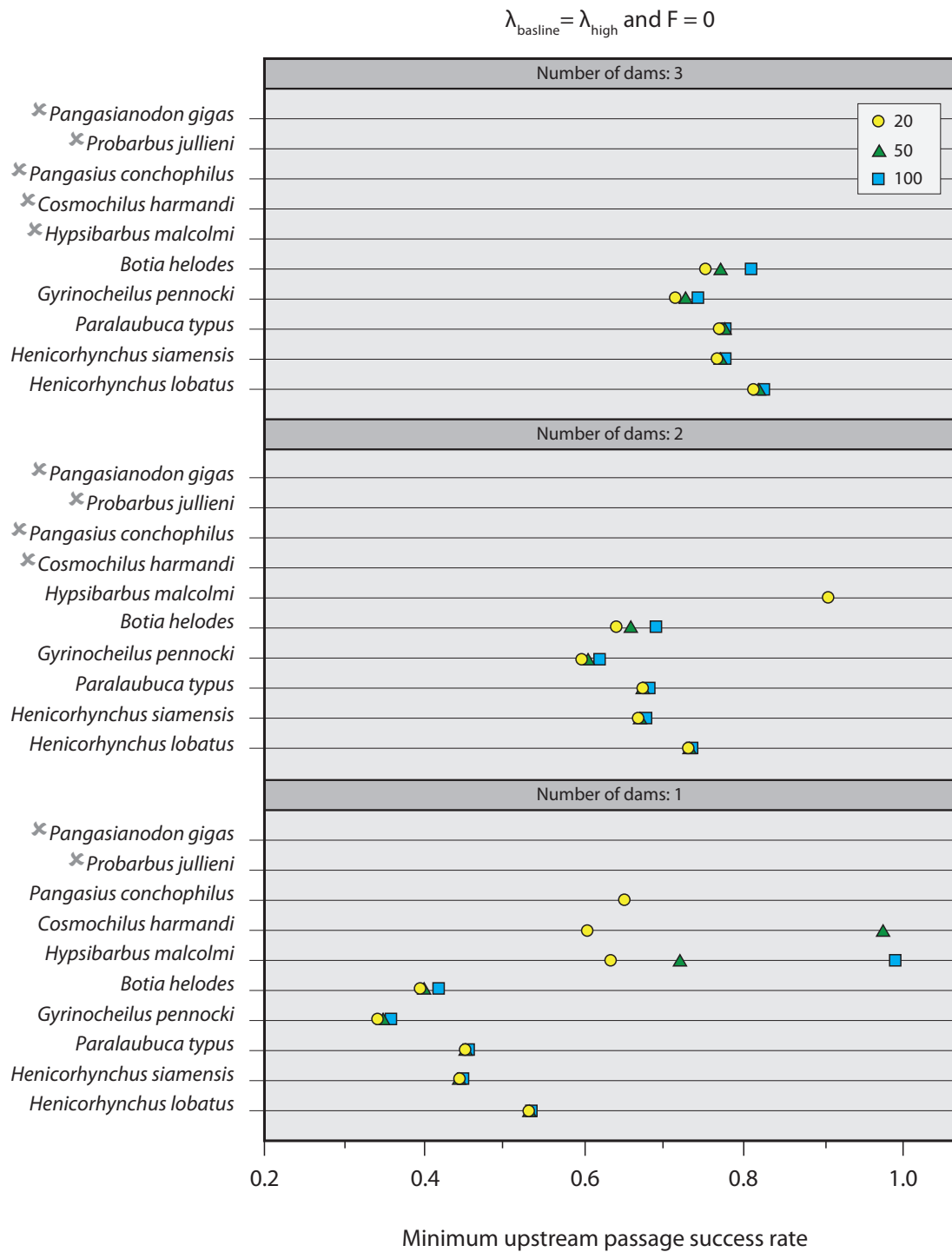


Figure 3.10 Minimum upstream passage success rate per dam for a species to be viable under no exploitation ($F=0$), and high reproductive potential condition. A cross beside a species name indicates that the population is not viable.

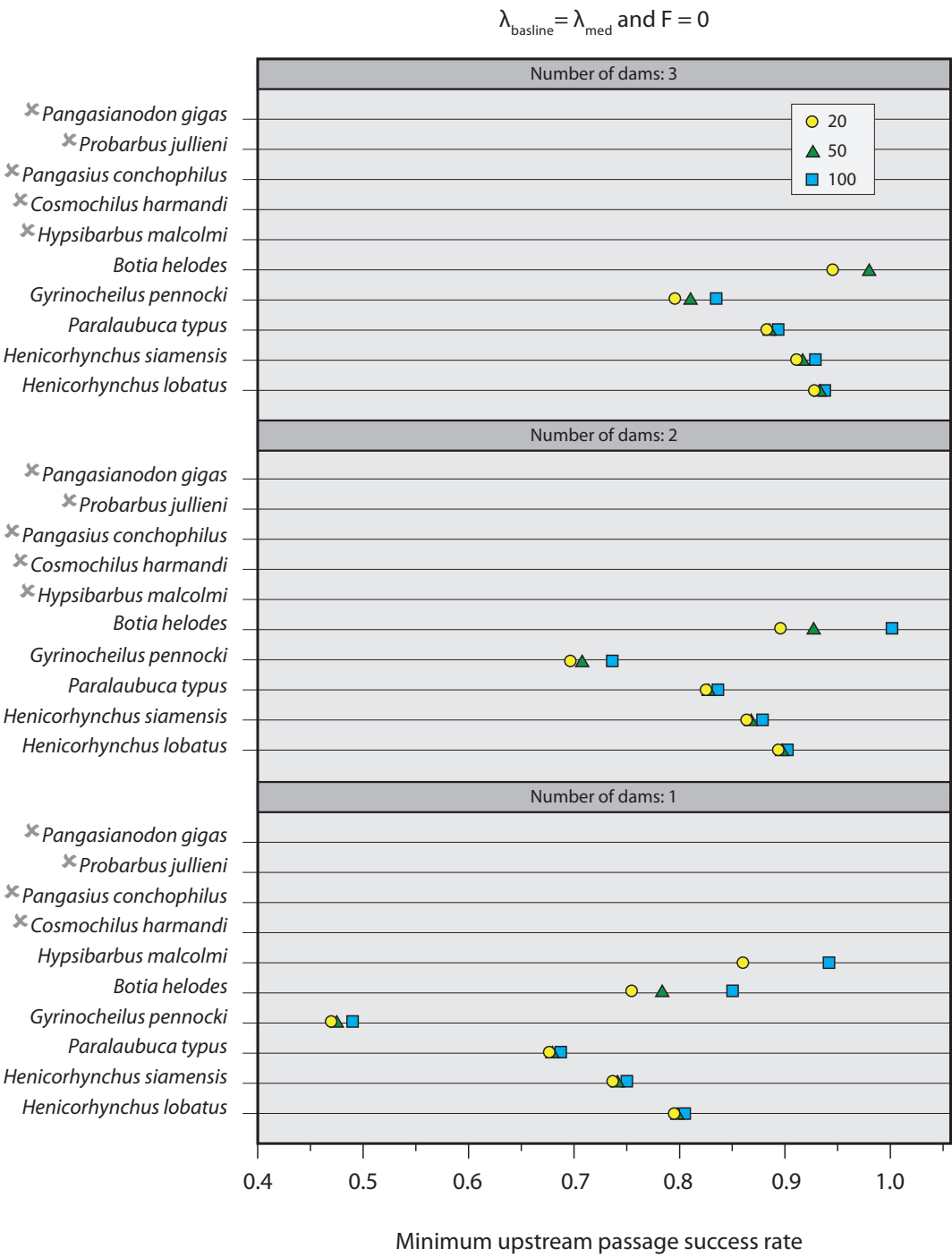


Figure 3.11 Minimum upstream passage success rate per dam for a species to be viable under no exploitation ($F=0$), and medium reproductive potential condition. A cross beside a species name indicates that the population is not viable.

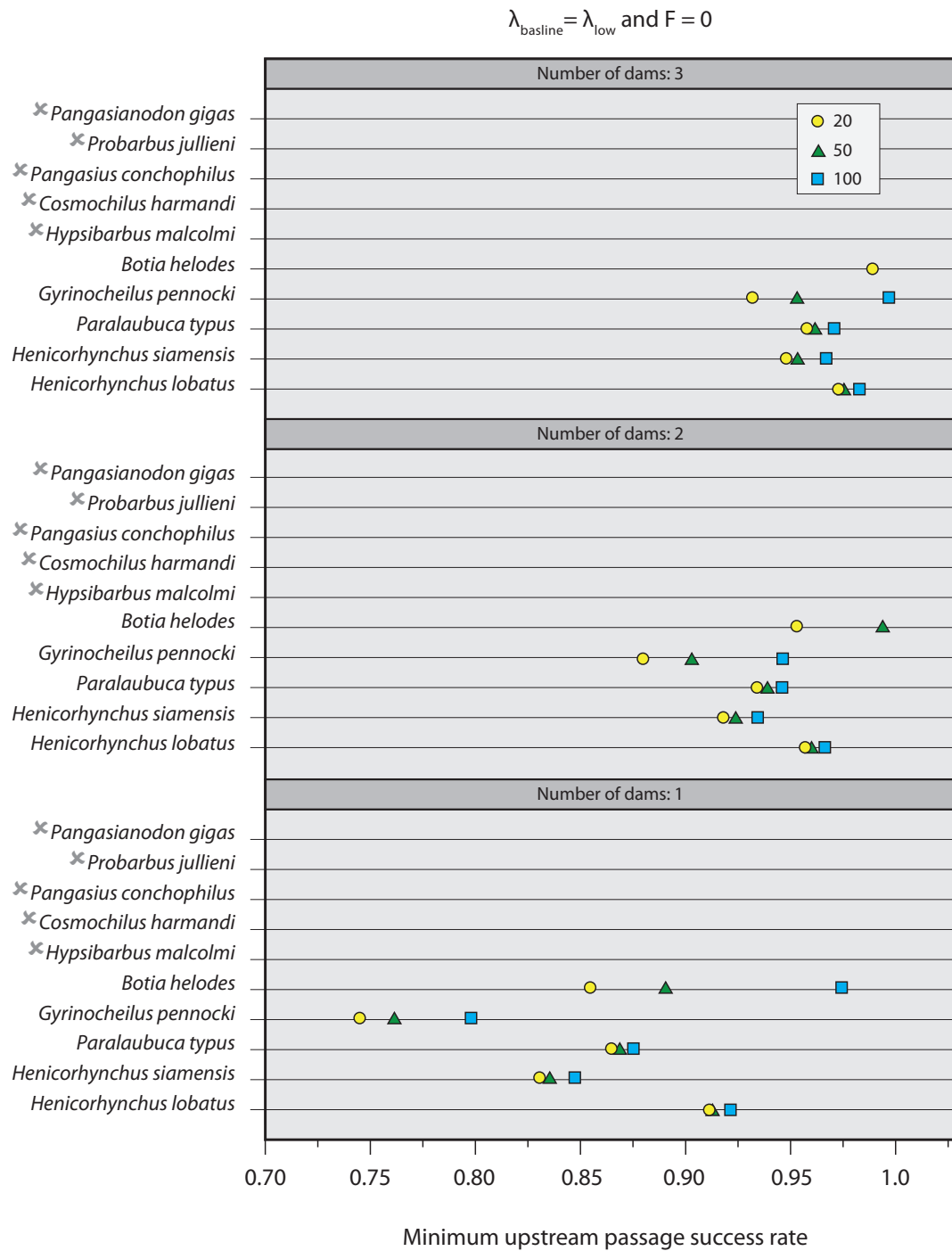


Figure 3.12 Minimum upstream passage success rate per dam for a species to be viable under no exploitation ($F=0$), and low reproductive potential condition. A cross beside a species name indicates that the population is not viable

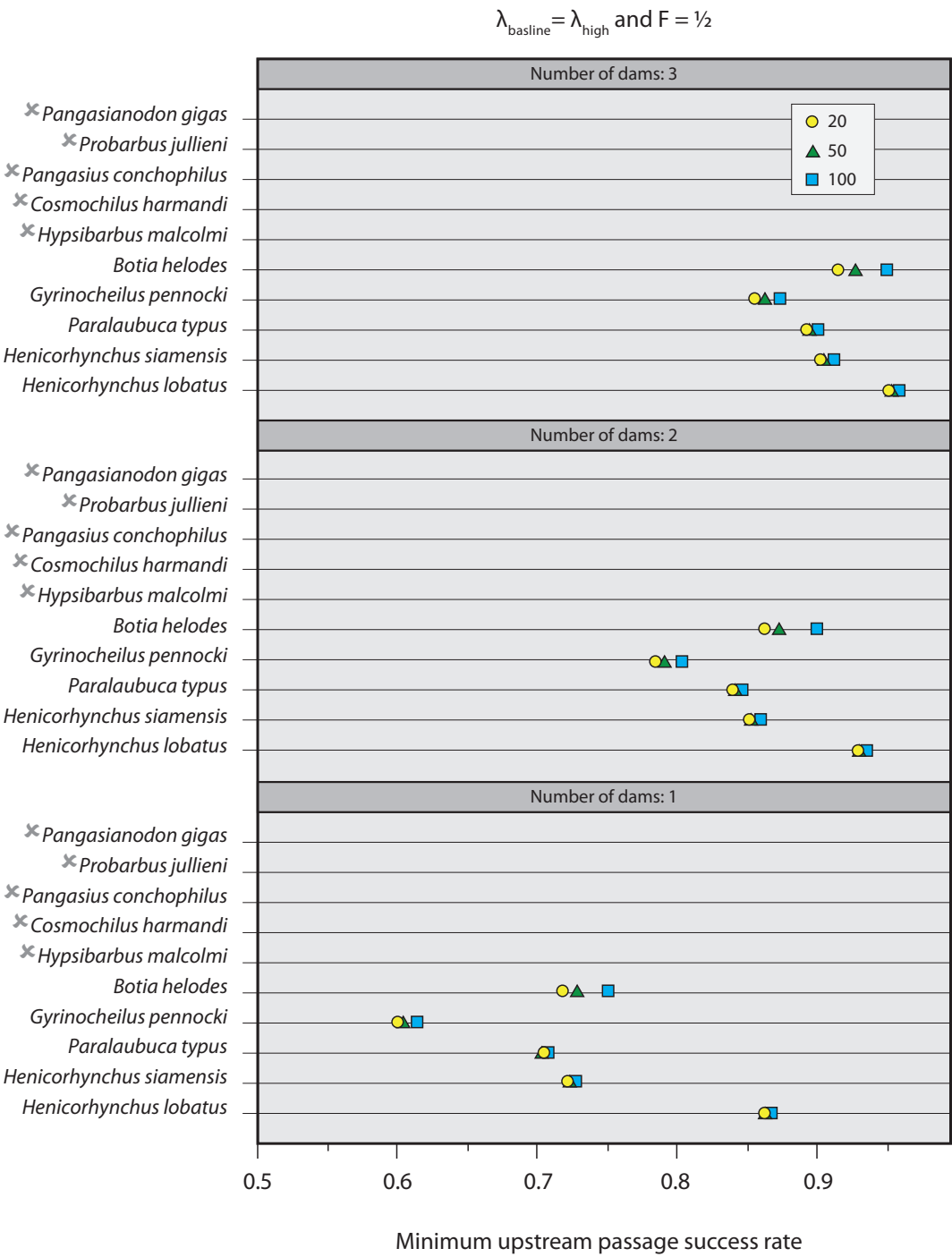


Figure 3.13 Minimum upstream passage success rate per dam for a species to be viable under exploitation ($F = 0.5$ for small species or 0.1 for large species), and high reproductive potential condition. A cross beside a species name indicates that the population is not viable

Under the low reproductive potential assumption, populations of only the smallest species remain viable but minimum upstream passage success rates increase significantly to a minimum of 75% for one dam and more than 90% for three dams (Figure 3.12).

Large species – no exploitation

It has already been reported that modelled populations of *P. jullieni* does not remain viable even under the most conservative assumptions and for a single dam crossing. Under the assumption that 25% of adults will pass downstream via turbines, populations of *P. gigas* also become unviable for a single dam and the minimum upstream passage success for the remaining three species exceeds 60%. Of the large species, only populations of *H. malcolmi* are predicted to remain viable if two dams must be crossed. In this case, upstream passage success must be in the order 90% when 25% of adults pass downstream via turbines. No large species are predicted to persist if three dams have to be crossed (Figure 3.10) or if their reproductive potential is low (Figure 3.13).

Under the low reproductive potential assumption, the model predicts that viable populations of *P. jullieni*, *P. gigas*, *P. conchophilus*, *H. malcolmi* and *C. harmandi* could not exist even for a single dam (Figure 3.12, lower panel).

The effect of reducing the downstream mortality by redirecting mature fish away from a turbine benefits the large compared to the small species. Populations of larger species are therefore more likely to respond to efforts to re-direct downstream migrating adults away from turbines. For example, the upstream passage rate for *H. malcolmi* must be close to 100% if all (100%) of the adults pass through the turbine. This becomes approximately 70% when 50% of the adults pass via the turbine and 60% when only 25% of the adults pass through the turbine (Figure 3.10, lower panel). For smaller species, redirecting fish away from a turbine appears to have little impact on the required minimum up-stream passage success rate. This reflects the relatively low rates of mortality experienced by small fish as they pass through the turbine compared to larger species.

So far we have examined how populations are predicted to respond only to barrier and passage effects of dams. In reality, the viability of populations will also be determined by prevailing rates of exploitation in the river system. After including estimates of these rates of exploitation in the model, minimum upstream passage success to maintain viable populations increase significantly.

Small species – with exploitation

For the small species under the assumption of high reproductive potential, minimum upstream passage success increases from approximately 35% (without exploitation) to approximately 60%–75% with exploitation depending upon the species for a single dam, rising to approximately 80%–90% for two and three dams respectively. Populations of these small

species would benefit only marginally from attempts to improve downstream passage survival (Figure 3.13 and Figure 3.14).

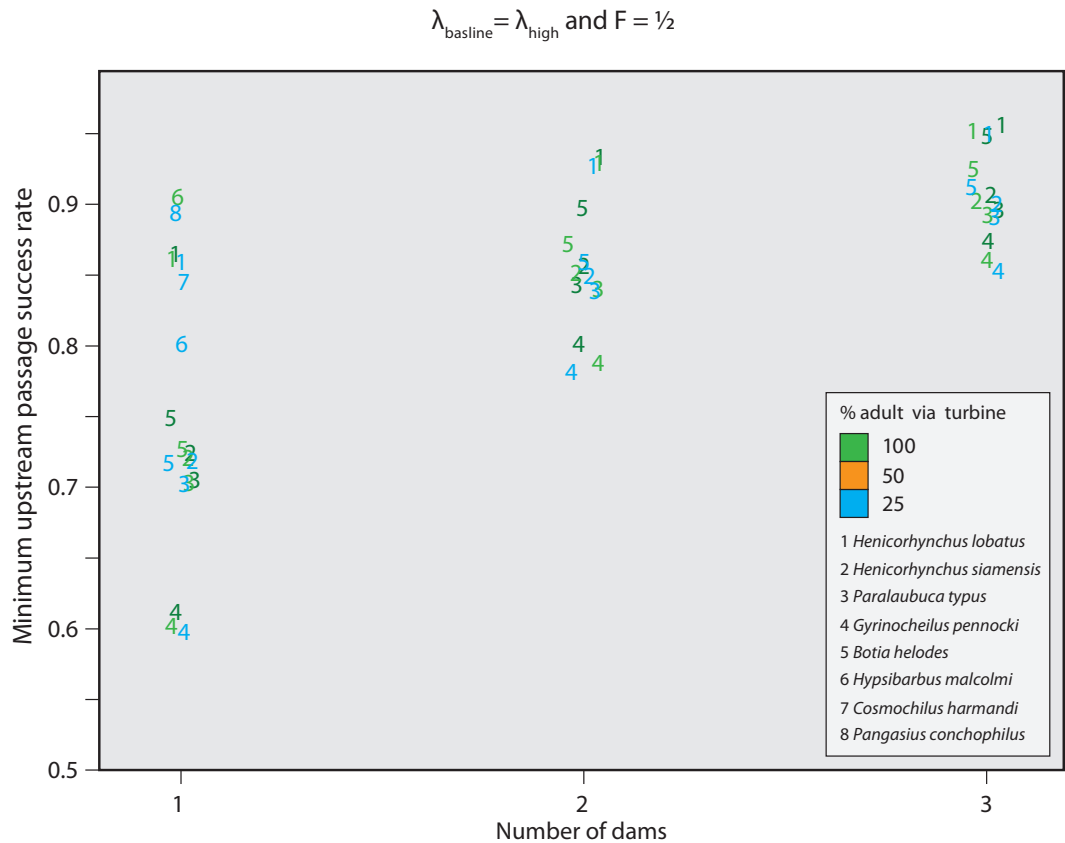


Figure 3.14 Minimum upstream passage success rate per dam for 1–3 dam crossings before arriving at a spawning habitat under the assumptions of $F = 0.5$ for small species or $F = 0.1$ for large species, high reproductive potential for all species, and 25, 50 or 100% of mature fish pass through a turbine. The species labels are jitter at each of the x-values to make them legible. Of the 10 species, *P. jullieni* and *P. gigas* are not included here because their populations are predicted to become unviable after only a single dam crossing.

Large species – with exploitation

Populations of large species are predicted not to persist under the selected rates of exploitation even if all upstream migrating adults pass successfully through a single dam capable of by-passing at least 75% of returning adults away from turbine intakes (Figure 3.13, lower panel).

Predicted minimum upstream passage success rates to maintain viable populations of the small and large model species are summarized for the most conservative high reproductive potential assumption in Table 3.1 and Table 3.2, respectively.

Table 3.1 Predicted minimum upstream passage success rate (%) to maintain viable populations of the five small species of fish included in the model under different assumptions and conditions.

Species	% of adults via turbine	1 Dam		2 Dams		3 Dams	
		NE	E	NE	E	NE	E
<i>H. lobatus</i> (Lesser silver mud carp)	25	53	86	73	93	81	95
	50	53	86	73	93	81	95
	100	53	87	73	94	82	96
<i>H. siamensis</i> (Siamese mud carp)	25	44	72	67	85	77	90
	50	44	72	67	85	77	90
	100	45	73	68	86	77	91
<i>P. typus</i> (Pelagic river carp)	25	45	70	67	84	77	89
	50	45	71	68	84	77	89
	100	45	71	68	85	78	90
<i>G. pennocki</i> (Spotted algae eater)	25	34	60	59	78	71	85
	50	34	60	60	79	72	86
	100	35	61	62	80	74	88
<i>B. helodes</i> (Tiger botia)	25	39	72	64	86	75	91
	50	40	73	66	87	77	93
	100	42	75	69	90	81	95

Note: For brevity only results for the most conservative high reproductive potential assumption are shown.
E—with exploitation (fishing); NE—No exploitation (no fishing).

Table 3.2 Predicted minimum upstream passage success rates (%) to maintain viable populations of the five large species of fish included in the model under different assumptions and conditions.

Species	% of adults via turbine	1 Dam		2 Dams		3 Dams	
		NE	E	NE	E	NE	E
<i>H. malcolmi</i> (Goldfin tinfoil barb)	25	63	80	X	X	X	X
	50	72	91	X	X	X	X
	100	99	X	X	X	X	X
<i>C. harmandii</i> (Green giant barb)	25	60	85	X	X	X	X
	50	97	X	X	X	X	X
	100	X	X	X	X	X	X
<i>P. concophilus</i> (Sharp-nosed catfish)	25	65	90	X	X	X	X
	50	X	X	X	X	X	X
	100	X	X	X	X	X	X
<i>P. jullieni</i> (Jullien's barb)	25	X	X	X	X	X	X
	50	X	X	X	X	X	X
	100	X	X	X	X	X	X
<i>P. gigas</i> (Mekong giant catfish)	25	X	X	X	X	X	X
	50	X	X	X	X	X	X
	100	X	X	X	X	X	X

Note: For brevity only results for the most conservative high reproductive potential assumption are shown.
E—with exploitation (fishing); NE—No exploitation (no fishing). X—indicates combinations give rise to non-viable populations.

These results indicate that for large species, attempts to improve downstream survival are relatively more important than those aimed at improving upstream passage success, whilst the converse is true for species with small maximum length. This is likely to raise significant challenges to designing engineering solutions to mitigate dam effects which typically have to be refined for species or groups of species sharing similar behaviour and swimming capacity often determined by body size (Clay, 1995).

Persistence time

For those species found to be unviable even under the most conservative or optimistic assumptions concerning their interaction with dams, we can estimate how long their populations will persist through time until they reach some specified proportion of their pre-dam level. In ecological studies, this proportion is typically chosen to be 0.5 where the time taken to reach this is termed the ‘population halving time’ or $t_{1/2}$. When $\lambda < 1$, the population is reduced by a constant fraction and declines exponentially (Brown and Rothery, 1994) as illustrated in Figure 3.15.

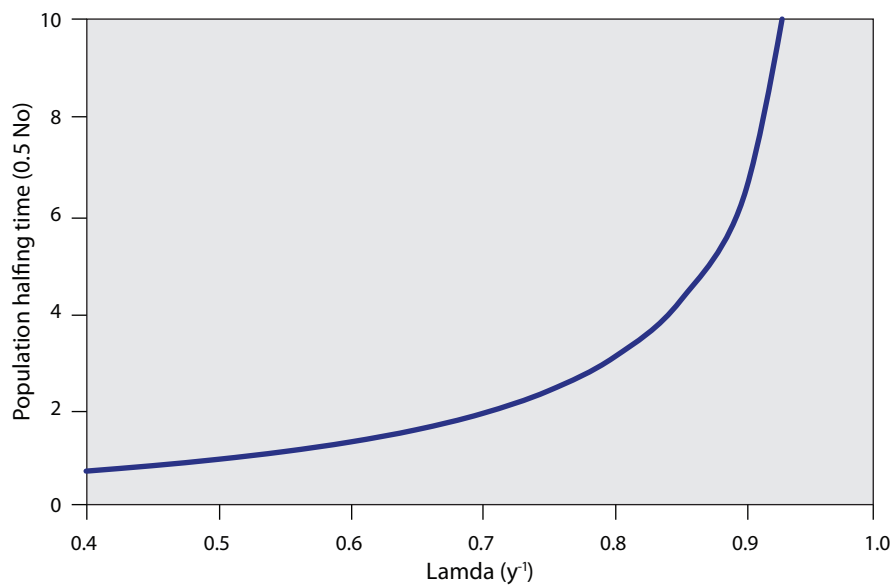


Figure 3.15 Population halving time $t_{1/2}$ plotted as a function of lamda.

The time for a population to decline by a factor of a half is given by:

$$t_{1/2} = \ln(1/2)/\ln(\lambda) \text{ for } \lambda < 1$$

Using Figure 3.15 we can estimate the halving time of the populations of each species using the estimates of λ illustrated in Figure 3.5 to Figure 3.9 or from Table 17 and Table 21 for different combinations of upstream passage success and downstream passage of adults via turbines. For example, under the low reproductive potential assumption, the predicted λ for

H. siamensis corresponding to 80% upstream passage success and 40% of returning adults by-passing the turbines would be approximately 0.8 (Figure 3.5, bottom left). Referring this value to Figure 3.15 gives a population halving time of approximately 2 years. Note that the contours of λ are for a single dam and exclude any fishing mortality effects ($F = 0$). Population halving times estimated from these figures are therefore likely to be very conservative.

Sensitivity analysis

The population growth rate (λ) and the minimum upstream passage rate which represent the two response variables of the matrix model, varied in sensitivity to several input parameters.

The annual population growth rate (λ) in response to the up and downstream passage rate changed depending on the three baseline values attributed to high, medium and low reproductive potential. In the matrix model, these levels influence the fecundity parameter. The results show that the contour plots for λ are insensitive to the three levels of reproductive potentials when a species is greater than 100 cm (*Hypsibarbus malcolmi*, *Cosmochilus harmandi*, *Probarbus jullieni* and *Pangasianodon gigas*). For the smaller species, contour values are sensitive to the different levels of reproductive potential or baseline values (Figure 3.5–Figure 3.9).

Model predictions of minimum upstream passage rates to maintain viable populations were sensitive to the number of fish passing through the turbine under the low reproductive potential assumption (Figure 3.12) but insensitive under high reproductive potential (Figure 3.10). These predictions were relatively insensitive to the proportion of adults passing downstream through the turbine only for small fish species. For example, the minimum passage rate for *Henicorhynchus lobatus* ($L_{\infty} = 15$ cm) ranged from 0.61 to 0.62 for the three alternative assumptions of the proportion of mature fish passing through the turbine (25%, 50% and 100%). Under the same condition but for a larger species, *Hypsibarbus malcolmi* ($L_{\infty} = 50$ cm), the minimum passage rate ranged from 0.85 to 0.99 (Figure 3.12).

Large species were found to be relatively insensitive to assumptions concerning reproductive potential compared to small species because: (i) differences between the three levels of potential were small for large species compared to small (see Table 2.8 on page 43) and (ii) mortality rates for large species exceed rates of reproduction after a single dam crossing in most cases. These populations are unable to persist and therefore appear insensitive to further increases in mortality arising from additional dam crossings.

4. Conclusions

Using the best available knowledge and data we have attempted to build a model to describe the spatial and temporal population dynamics of a set of highly migratory fish populations in response to exploitation and obligatory upstream and downstream migrations through dam structures to complete their life-cycles.

We believe this is the first attempt to construct a model that explicitly accounts for size-(age) dependent migrations between critical habitat via multiple dam structures on the dynamics and sustainability of highly migratory iteroparous fish species.

Without the necessary observations, we have been unable to validate the model predictions relating to dam passage effects on the viability of fish populations in the basin. However, the model does appear to effectively simulate inter-annual changes in the size structure of fish populations observed under catch assessment surveys and the passage mortality predictions are consistent with those reported by other workers. The model provides an effective and flexible means to explore, under explicitly stated assumptions and uncertainty, the likely response of highly migratory fish stocks to the barrier and passage effects of multiple mainstream dam structures and help identify strategies to mitigate these effects.

The model has been applied to examine the response of ten highly migratory fish species exhibiting a wide range of life-history characteristics. We therefore believe that we have captured the full range of likely responses of fish stocks in the basin. The full suite of required population parameters for two species (*C. microlepis* and *M. rosenbergii*) initially selected for modelling could not be estimated and therefore these two species were subsequently omitted.

Based upon our assumptions concerning the life-cycles of the selected species and the longitudinal distribution of their critical habitat in relation to proposed dam structures, we have predicted minimum upstream passage success rates of spawning (adult) fish to maintain viable populations under a range of different assumptions concerning the survival rates of returning adults and juveniles as they return to downstream feeding and refuge habitat.

Adults of small species such as *H. siamensis*, *P. typus* and *B. helodes* experience relatively low mortality rates during their return migrations from upstream spawning habitat ranging from approximately 2%–15% per dam crossed assuming all individuals pass through the turbines. This declines to less than 5% under the assumption that 75% of individuals could be safely bypassed via spillways or by-pass channels.

Spawning adults of large species on the other hand experience very high rates of mortality if they pass through turbines reaching 100% probability of mortality for *P. gigas*, *P. jullieni* and 80% for *P. conchophilus*.

Because downstream survival rates are largely length-dependent, investment in solutions to improve downstream survival would therefore generate greater benefits for large compared to small species.

The juveniles (and adults) of all species are modelled to return to downstream to feeding habitat between one and three months after spawning. At this time the mean length of juveniles varies between 1 cm and 6 cm depending upon the species. Due to their small size, their turbine mortality rates are predicted to be very low ($< 2\%$). This has important implications both for the model predictions and mitigation strategies. Firstly, the model predictions will be insensitive to assumptions surrounding the proportion of juveniles that pass through dam turbines. In all our simulations we assume this proportion to be 1.0 (100%) due to the limited capacity of juveniles to avoid entrainment (swimming capacity is a function of fish length) but also the ability of engineers to effectively screen turbines from entrainment of small individuals without compromising turbine efficiency (Larinier, 2008). Secondly, it suggests that mitigation strategies aimed at improving the downstream survival of juveniles are likely to generate only marginal benefits often after very high research, development and investment cost. By-pass efficiency estimates from other river systems appear to be highly variable, ranging from 0–100% but relate mainly to downstream juvenile passage (Table 4.2 on page 70).

Attempts to improve downstream survival should focus upon the adults of large and, to a lesser extent, also small species. However, it is conceivable that engineering solutions will have to be near perfect for the very largest species such as *P. gigas*, *P. jullieni* and *P. conchophilus*, *C. harmandii*, and *H. malcolmi*.

For exploited populations crossing only a single dam and assuming that 75% of all returning adults could be safely re-directed away from the turbines, only *P. conchophilus*, *C. harmandii*, and *H. malcolmi* are predicted to persist ($\lambda > 1$) if their upstream passage through the dam is in excess of 80%. None of the large species are predicted to persist if two or more dams must be crossed even if their upstream migrations were completely unhindered (i.e. 100% passage success rate).

P. jullieni is predicted not to persist after just a single dam crossing, even without exploitation. Reservoir dams along the Perak River, Malaysia are reported to have blocked the movements of *P. jullieni* and reduced breeding and spawning grounds (Jackson and Marmulla, 2001). *P. gigas* is predicted to persist if: (i) only one dam is to be crossed, (ii) fishing for this species was banned ($F = 0$); (iii) at least 90% upstream passage efficiency was achieved and, (iv) if all returning adults could be safely re-directed away from dam turbines (100% downstream survival of adults).

With potentially increasing rates of exploitation from a growing basin population and the prospect of multiple dam obstructions, fears surrounding the persistence of *P. gigas* raised by Mollot (2008) therefore appear warranted and are likely to apply to other large species.

The strong size-dependent downstream mortality effects predicted by the model coupled with semelparous versus iteroparous reproductive behaviour may explain why attempts to mitigate

dam impacts on Pacific salmon populations in the Columbia River basin have been relatively successful compared to those in tropical systems where most species exhibit iteroparous reproductive behaviour. Not only are they strong swimmers able to negotiate fish passes with relative success, but adult Pacific salmon die shortly after spawning and therefore the effects of downstream dam passage mortality on returning adults are of no consequence to the viability or sustainability of their populations. In river systems such as the Mekong, adults of medium and large size iteroparous species may need to undertake several spawning migrations in their lifetime to maintain viable populations. It is these large adult fish that experience significant rates of mortality during their downstream passage through dams.

Based upon the experiences of mitigation in the Columbia Basin following some 30 years of research and development at a cost of more than US\$7 billion (Williams, 2008), the prospects for achieving these high rates of passage efficiency in such a short period of time appear remote particularly given the wide range of fish life-history strategies, behaviour and swimming capacities of the threatened species. This may prompt the need for more radical solutions to mitigation that allow un-hindered bi-directional fish migrations to be conceived such as dedicated natural river (by-pass) channels (Ferguson pers. comms.). However these are likely to require high capital expenditure and may compromise the economic viability of some projects. In some upstream locations such measures may be impossible where the channel is flanked by hills or mountains.

Even if the loss of large species could be absorbed or justified in some way, upstream passage efficiency would need to exceed 60% to maintain viable exploited populations of even the smallest species regardless of the performance of any downstream by-pass systems that might be installed. This minimum upstream passage success rate would need to be further raised to more than 80%–90% if adult fish were obliged to cross two or more dams to reach critical upstream spawning habitat. We were unable to find evidence in the literature to suggest that these rates of passage success can be achieved (Table 4.1 on page 70).

Mainstream dams in the LMB therefore have the potential to diminish fish diversity and the size structure of the community thereby potentially impacting upon ecosystem integrity and functioning. Overall catch value may also decline if large, valuable, highly migratory species no longer persist at levels that are economically attractive to fishers. Populations of small species that respond rapidly to, or ‘track’, environmental variation may also decline further, diminishing their resilience to climate change and leading to greater inter-annual variability in landings. However, potential ‘prey-release’ effects where abundance of small prey species increases in response to a decline in the abundance of large piscivorous confound such predictions.

Minimum upstream passage success rates under different assumptions concerning downstream by-pass efficiency, numbers of dams and rates of exploitation appear to be well described by λ (Figure 4.1 on page 73). With knowledge of λ , these types of plots can readily provide approximate estimates of minimum upstream passage success for other species not examined here under different assumptions concerning the number of dams and the proportion of adults passing downstream through turbines.

Table 4.1 Summary of reported upstream passage success in other river basins.

Location	Species	Life stage	Pass type	UPS %	UPM %	Reference
Columbia River USA	NS	NS	Fish lock	1.5		Larinier (2001)
Brazil	NS	NS	NS	2		Larinier (2001)
Don River Russia	Acipenser	NS	Sluice	67*		Pavlov (1989)
Don River Russia	NS	NS	Sluice	44*		Pavlov (1989)
BD Columbia River USA	Pacific lamprey	Adult	Fishway	50*		Ferguson et al (2005)

Note: UPS – Upstream passage success; UPM – Upstream passage mortality. * refers to proportion of ‘approaching fish’ that successfully pass. NS = not specified.

Table 4.2 Summary of reported downstream passage success (DPS) and mortality (DPM) in other river basins.

Location	Species	Life stage	Pass type	DPS %		DPM %		Reference
				Lower	Upper	Lower	Upper	
IHD, Snake River USA	NS	NS	Bypass	3	17			Goodwin <i>et al.</i> (2006)
WD Columbia River USA	NS	NS	Bypass	3	17			Goodwin <i>et al.</i> (2006)
LGD, Snake River USA	NS	NS	Bypass	0	78			Goodwin <i>et al.</i> (2006)
Snake River dams USA	<i>O. tshawytscha</i>	0+ migrants	Bypass	69	78			Whitney <i>et al.</i> 1997
Snake River dams USA	<i>O. mykiss</i>	0+ migrants	Bypass	82	92			Whitney <i>et al.</i> 1997
Snake River dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Bypass			1	2	Muir <i>et al.</i> 2001
Columbia and Snake River Dams	Salmonids	Juvenile	Bypass			0	6	Ferguson <i>et al.</i> 2005
IHD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Bypass		57			Ferguson <i>et al.</i> 2005
DD, Columbia River USA	NS	NS	Bypass	6	55	3	11	Ferguson <i>et al.</i> 2005
BD, Columbia River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Bypass	13	83			Ferguson <i>et al.</i> 2005
RRD, Columbia River USA	Salmonids	Juvenile	Bypass	31	68			Ferguson <i>et al.</i> 2005
LGD, Snake River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Bypass	56	69			Ferguson <i>et al.</i> 2005
Kuban River Russia	NS	NS	Bypass (floating boom)		67			Pavlov (1989)
Russia	NS	NS	Bypass (hydraulic screen)	55	100			Pavlov (1989)
Connecticut River USA	Salmonids	Smolts	Bypass (louvre screen)		97			Larinier (2001)
Connecticut River USA	Clupeids	Juveniles	Bypass (louvre screen)		86			Larinier (2001)

Location	Species	Life stage	Pass type	DPS %		DPM %		Reference
				Lower	Upper	Lower	Upper	
Ural River Russia	NS	Juvenile	Bypass (natural)		82			Pavlov (1989)
USA/France	NS	NS	Bypass (surface)	60	85			Larinier (2001)
Gave de Pau France	Salmonids	NS	Bypass**	34	100			Larinier 2008
LGD, Snake River USA	NS	NS	Non turbine routes		90			Ferguson <i>et al.</i> 2005
Snake River dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Non turbine routes		94			Muir <i>et al.</i> 2001
DD & BD, Columbia River USA	<i>O. mykiss</i>	Adult	Sluiceway	64	89			Ferguson <i>et al.</i> 2005
Columbia River USA	Salmonids	Juvenile	Spillway			0	37	Larinier (2001)
IHD, Snake River USA	NS	NS	Spillway	78	89			Goodwin <i>et al.</i> (2006)
WD Columbia River USA	NS	NS	Spillway	0	61			Goodwin <i>et al.</i> (2006)
LGD, Snake River USA	NS	NS	Spillway	5	89			Goodwin <i>et al.</i> (2006)
Snake and Columbia Rivers USA	Salmonids	Juvenile	Spillway			0	27	Muir <i>et al.</i> 2001
Snake River dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway		41			Muir <i>et al.</i> 2001
Snake River dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway			0	2	Muir <i>et al.</i> 2001
IHD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Spillway	64	96			Ferguson <i>et al.</i> 2005
MND, Columbia River USA	<i>O. tshawytscha</i>	Juvenile	Spillway	47	49			Ferguson <i>et al.</i> 2005
JDD, Columbia River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway	46	92			Ferguson <i>et al.</i> 2005
DD, Columbia River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway	51	88			Ferguson <i>et al.</i> 2005
BD, Columbia River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway	22	70			Ferguson <i>et al.</i> 2005
Columbia and Snake River Dams	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway			0	2	Whitney <i>et al.</i> 1997
Snake River Dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway			0	7	Ferguson <i>et al.</i> 2005
IHD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Spillway			0	12	Ferguson <i>et al.</i> 2005
LGD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Spillway				7	Ferguson <i>et al.</i> 2005
LMD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Spillway			2	17	Ferguson <i>et al.</i> 2005
MND, Columbia River USA	<i>O. tshawytscha</i>	Juvenile	Spillway			2	7	Ferguson <i>et al.</i> 2005

Location	Species	Life stage	Pass type	DPS %		DPM %		Reference
				Lower	Upper	Lower	Upper	
JDD, Columbia River USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Spillway			1	9	Ferguson <i>et al.</i> 2005
DD, Columbia River USA	<i>O. tshawytscha</i> <i>O. kisutch</i>	Juvenile	Spillway			0	24	Ferguson <i>et al.</i> 2005
BD, Columbia River USA	<i>O. tshawytscha</i>	Juvenile	Spillway			0	13	Ferguson <i>et al.</i> 2005
LGD, Snake River USA	NS	NS	Spillway	38	86			Ferguson <i>et al.</i> 2005
DD, Columbia River USA	<i>O. mykiss</i>	Adult	Spillway		99			Ferguson <i>et al.</i> 2005
IHD, Snake River, USA	NS	NS	Turbine	10	21			Goodwin <i>et al.</i> (2006)
Snake & Columbia Rivers USA	Salmonids	Juvenile	Turbine			2	19	Muir <i>et al.</i> 2001
Snake River dams USA	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Turbine			7	14	Muir <i>et al.</i> 2001
RRD, Columbia River USA	<i>O. tshawytscha</i>	Juvenile	Turbine				7	Mathur <i>et al.</i> 1996
LGD, Snake River USA	<i>O. tshawytscha</i>	Juvenile	Turbine				5	Normandeau <i>et al.</i> 1995
Columbia and Snake River Dams	<i>O. tshawytscha</i> <i>O. mykiss</i>	Juvenile	Turbine	64	89	0	28	Ferguson <i>et al.</i> 2005
NS	Salmonids	Juvenile	Turbine (Francis)			5	90	Larinier (2001)
NS	Salmonids	Juvenile	Turbine (Kaplan)			5	20	Larinier (2001)
LMD, Snake River USA	<i>O. tshawytscha</i>	Adult	Turbine (Kaplan)			22	57	Ferguson <i>et al.</i> 2005
WD Columbia River USA	NS	NS	Turbines	32	91			Goodwin <i>et al.</i> (2006)
LGD, Snake River USA	NS	NS	Turbines	8	96			Goodwin <i>et al.</i> (2006)

Notes: IHD–Ice Harbor Dam; WD–Wanapum Dam; LGD–Lower Granite Dam; RRD–Rocky Reach Dam; MND–McNeary Dam; JDD – John Day Dam; DD–Dalles Dam; BD–Bonneville Dam; LMD–Lower Monumental Dam.

* corresponds to 33 % of flow via spillway; ** small scale hydro-electric plant.

Where no lower range is given, upper value refers to single estimate.

Whilst our model predictions were not subject to a systematic sensitivity analysis by applying incremental changes to each base parameter estimate in turn, the study did explore a large ‘parameter space’ by including a wide range of fish life history strategies in the model and by testing the possible range of passage efficiency both upstream and downstream. We also explored the sensitivity of the model predictions to uncertainty surrounding the estimated population growth rate by incorporating a range of values around the estimate of population doubling time given in FishBase. Population responses with and without mortality due to fishing were also examined to determine the sensitivity of the model predictions to uncertainty surrounding existing rates of exploitation.

As part of a regional stakeholder consultation on hydropower held in Vientiane, 25–27 September 2008, an expert group of fisheries biologists and ecologists concluded that dams in the middle and lower LMB will have the largest impacts on fisheries compared to those in the

upper part of the basin (Dugan, 2008). The spatial distribution of estimates of total annual catch aggregated across all species was used to support this conclusion (Figure 4.2 on page 74).

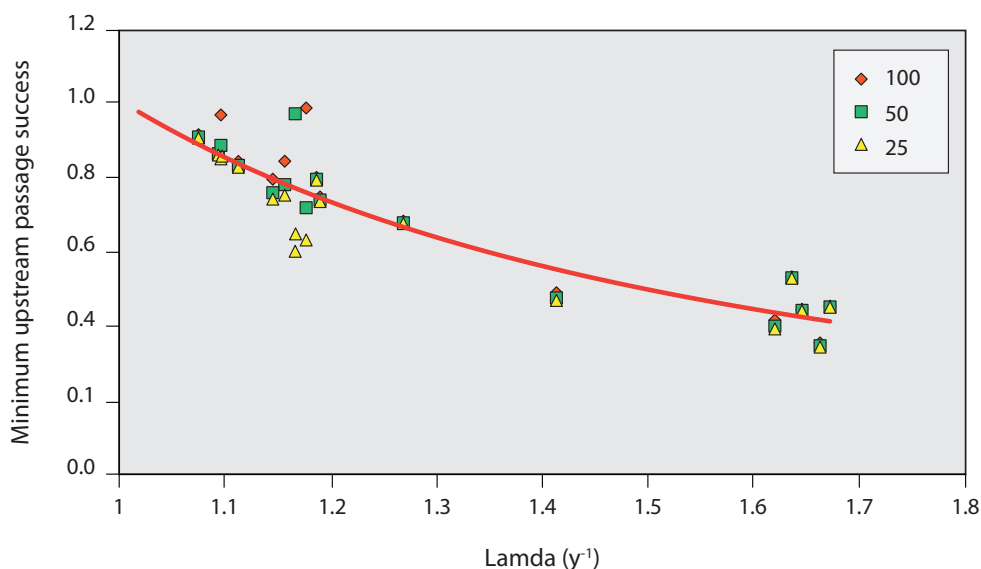


Figure 4.1 Minimum upstream passage success (UPS) plotted as a function of λ for the model species estimated from population doubling times quoted in FishBase for downstream adult turbine passage proportions of 100 %, 50%, and 25%, a single dam crossing and no exploitation ($F = 0$) with fitted power function. $UPS = 1.01\lambda^{-1.41}$, $R^2 = 0.87$.

In other words, the impact of a mainstream dam is hypothesised to decline as a function of its position upstream from the river mouth so that dams built in the upper reaches of rivers will have less impact than those built in downstream locations.

However, as described in Section 2.1, not all species of fish are equally vulnerable to the barrier and passage effects of dams, and therefore it may be potentially misleading to use catch data aggregated across all species and seasons to draw such conclusions. The lower Mekong is likely to have proportionally fewer vulnerable species compared to the upper Mekong because the diverse floodplain habitat characteristic of the lower Mekong supports species of fish that do not undertake extensive migrations to upstream habitat. Many species in this region have evolved morphological and physiological adaptations to inhabit the floodplain throughout the year. It is the adults (and juveniles) of those species that are obliged or have a comparative advantage to undertake significant seasonal upstream and downstream migrations between the lower and upper reaches of the Mekong that are most vulnerable. The adult spawning migrations of fish belonging to these species support some of most important, but highly seasonal fisheries in Lao PDR including the fishery at Khone Falls.

These highly migratory species referred to above and which form Guilds 2 & 3 in this report have a basin-wide range (See Figure 2.6 on page 23 and Figure 45). For these species, the hypothesis that dams built in the upper reaches of rivers have less impact than those built in

downstream locations assumes: (i) the distribution of spawning habitat for these species is either uniform throughout the range of the species, skewed towards the downstream reaches, or absent from upstream reaches, and/or (ii) one or more discrete populations of the species exist in the system.

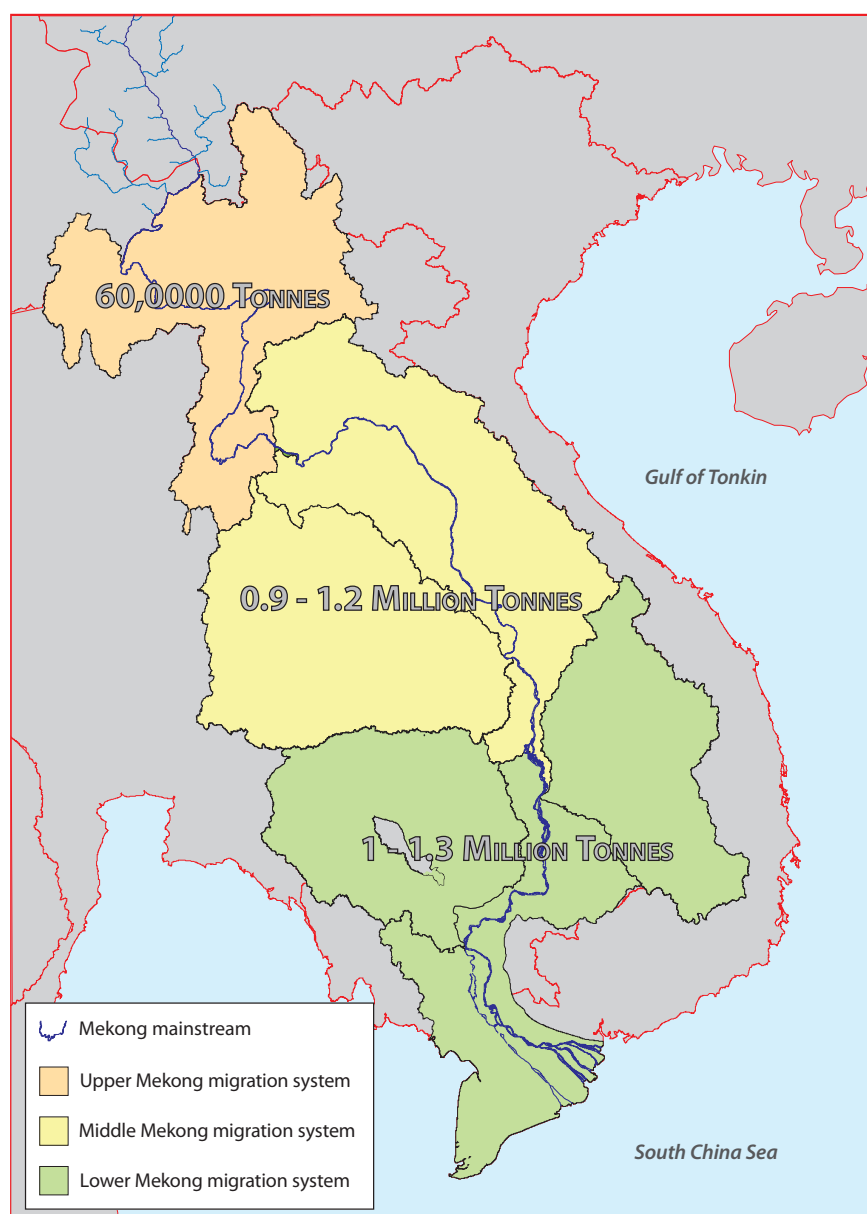


Figure 4.2 Estimates of total annual catch aggregated across all species in the upper, middle and lower Mekong river.

Source: Conclusions from an Expert Group Meeting on Dams as barriers to fish migration in the Mekong mainstream, and possibilities for mitigation, Vientiane, Lao PDR, 22–23 September 2008.

Note: that the catch estimates have been revised (see Barlow *et al.* 2008).

We believe data and information concerning both the distribution of spawning habitat in the basin and the population structure are currently inadequate to determine if these assumptions

are reasonable for most of the species examined here. We have adopted a conservative or precautionary approach by assuming a single population structure and that all spawning habitat is distributed above the uppermost dam.

It should also be borne in mind that fewer options to mitigate the barrier effects of dams may exist in the upper reaches of the basin particularly where the channel is flanked by hills or mountains and the channel gradient is steep requiring greater dam heights.

The model predictions are likely to be most sensitive to assumptions concerning the distribution of spawning habitat which effectively determines the proportion of the population that is likely to experience barrier and passage effects. The results of the MRC's on-going basin-wide ichthyoplankton survey will help determine the validity or otherwise of this assumption and thereby help guide alternative assumptions for future modelling work. Model simulations under different assumptions concerning the distribution of critical habitats (e.g. normal, uniform, skewed...etc) in relation to dam locations were planned at the onset of the study but these were not conducted due to time constraints. Further insights into habitat distribution will also allow us to explore the relative impacts of specific dam projects in relation to their upstream location and allow us to test the hypothesis that dam projects located upstream have less impact on fish stocks than those built downstream.

The model also assumes that λ is constant through time. In reality, this is unlikely since rates of growth, survival and reproduction are likely to vary in response to environmental conditions, including flood timing, extent and duration.

4.1 Future Research Priorities – Phase II

To reduce and report uncertainty in the model predictions we propose that a second phase of model development should include the following activities:

Critical habitat distribution

Incorporate the findings of the MRC's ichthyoplankton survey designed to map the distribution of spawning habitat in the basin. Survey data should become available towards the end of 2009. This would effectively help to reduce model uncertainty i.e. mis-specification of the model structure. This is currently one of the most uncertain yet influential structural elements of the model. At a minimum, the model simulations should be repeated using a range of alternative assumptions concerning the distribution of habitat as outlined above to illustrate the uncertainty in the model predictions arising from these assumptions.

Catadromous life cycles

We were unable to parameterize the model for the catadromous *M. rosenbergii* included in our original selection of model species (Chapter 2.1). We therefore recommend that any future model development include alternative species to determine if populations of catadromous species respond in the same manner to barrier and passage effects as species belonging to Guilds 2 and 3.

Incorporation of stochastic population growth

The population model developed here could be extended to incorporate vital rates as function of the environmental variables, such as flow levels, oxygen concentration and water temperature to illustrate the effect of process uncertainty (random variability) on the model predictions. This would allow the user to couple hydrological and population model to forecast population size at finer time scale. Furthermore, such a model component could be applied to population viability analysis, a method of risk assessment of threatened species.

Other related research to reduce uncertainty in model predictions

Few estimates of fishing mortality (F) exist for species exploited in the LMB. The analysis of length-frequency data from a well-designed short duration basin-wide survey could provide more accurate and precise estimates of fishing mortality for the model species. Estimates of fish fecundity at length could also be derived on the basis of similar short term biological surveys (see Bagenal, 1978). Further research is required to determine the population structure of threatened species to ensure the correct specification of the model structure (to minimize model uncertainty). Mitochondrial DNA analyses of the type described by Hurwood *et al.* (2006) appear promising requiring little time and few resources.

The blade-strike model used to estimate the mortality rates of fish as they pass downstream through dam turbines was based upon turbine geometry and blade rotation speeds specific to the Sikfors Power Station, Sweden (see Section 2.4). During reviews of this report, it became apparent that the rotation speed of this turbine is uncommonly high compared to most Kaplan type turbines at 167 rpm compared to 75 rpm, respectively (Ferguson per comms). This is potentially significant because blade rotation speed affects the probability of blade-strike and hence mortality. However, subsequent investigations revealed that the probability of mortality from blade strike events was insensitive to the higher turbine rotation speed for all five small species of fish examined (< 25 cm total body length) and for large individuals (>100 cm total body length) of the five large species examined. The probability of mortality for fish with body lengths ranging from 50 cm and 100 cm were most sensitive to blade rotation speed, experiencing up to a maximum of approximately 30% lower mortality at the lower rotation speed. During the final revisions of the report, it was learnt that a typical turbine rotation speed for the Mekong projects is likely to be in the order of 95 rpm (Haas pers.com). Therefore, the likely overestimation of mortality rates for this size category would be less than 30%.

It was decided not to re-run all the simulations with the revised blade-strike model before final reporting because: (i) the general conclusion that engineering solutions to facilitate upstream fish passage will need to be almost perfect ($> 80\%$ – 95% efficient for two or more dams) remains unchanged; (ii) other potential sources of downstream passage mortality via spillways and by-passes were excluded from the model but can be significant (Table 3.1 on page 63); (iii) the existence of other sources of uncertainty in the model including spawning habitat distribution and rates of exploitation.

It is however recommended that any future model development should aim to improve the reliability of the model predictions by revising the existing blade-strike model with turbine geometry and rotation speeds more typical of the actual proposed projects once they have been finalised by the developers and engineers.

Summary

Table 16 summarises the sources of uncertainty surrounding the model predictions, and recommended action to reduce or report this uncertainty. Uncertainty surrounding the model predictions arises from a combination of process, observation or measurement, and model uncertainty. The table also indicates the relative importance of these sources to the overall study conclusions, recommended action, and relative required time and resources.

Table 4.3 *Sources of uncertainty surrounding model predictions and recommended action.*

Sources of uncertainty	Description and (importance)	Action, comments and (required resources)
Model Uncertainty (mis-specification of the model structure)	Distribution of spawning habitat relative to dam locations (***)	To report uncertainty repeat simulations with different assumptions concerning the distribution of spawning habitat. May require some re-structuring of the existing model (++)
		To reduce uncertainty repeat simulations incorporating spawning habitat distribution based upon results of ‘Ichthyoplankton Survey’. May require some re-structuring of the existing model (+++).
	Catadromous life cycles (*).	To reduce uncertainty repeat simulations using catadromous life-cycle model for catadromous species. Catadromous species relatively unimportant in terms of landings in the LMB. May require some re-structuring of the existing model (++)
	Population structure (***)	- To report uncertainty repeat simulations with different assumptions concerning the population structure of each species. Will require re-structuring of the existing model (+++). - To reduce uncertainty repeat simulations with appropriate population structures for each species based upon DNA studies. Will require a basin-wide tissue sampling programme and re-structuring of the existing model (+++).

Sources of uncertainty	Description and (importance)	Action, comments and (required resources)
Process Uncertainty (random variability in population dynamics)	Environmental effects (*).	To report uncertainty arising from environmental variation repeat simulations incorporating vital population growth rates as function of the environmental variables such as flow levels, oxygen concentration and water temperature (++).
Observation or Measurement Uncertainty (arises from the collection or measurement of variables)	Estimates of turbine blade strike mortality (**).	To reduce uncertainty repeat simulations incorporating turbine rotation speeds for Mekong projects provided by project developers (+). But note that other sources of downstream mortality are not included.
	Fishing mortality, F (*).	To reduce uncertainty repeat simulations incorporating estimates of F for the model species derived from length-frequency samples across the basin (++).
	Fecundity estimates (*)	To reduce uncertainty repeat simulations incorporating estimates of fecundity at length for the model species (++).

Note: Relative importance of sources of uncertainty for study conclusions: * low; ** medium; *** high. Required time and resources: + low; ++ medium; +++ high.

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Appendix 1. List of species belonging to the vulnerable guilds 2, 3, 8, and 9

Family	Scientific Name	Guild	Guilds 2,3,8,9			All Guilds (121607 kg)		Model species
			Total Weight (kg)	Cumulative weight (kg)	Cumulative (%)	% of total catch	Cumulative %	
Cyprinidae	<i>Henicorhynchus siamensis</i>	3	9838	9838	21	8.09	8.1	X
Cyprinidae	<i>Henicorhynchus lobatus</i>	3	4946	14784	32	4.07	12.2	X
Cyprinidae	<i>Cosmochilus harmandi</i>	3	3489	18273	39	2.87	15.0	X
Pangasiidae	<i>Pangasius conchophilus</i>	2	2516	20789	44	2.07	17.1	X
Cyprinidae	<i>Paralaubuca typus</i>	3	2013	22801	49	1.65	18.8	X
Gyrinocheilidae	<i>Gyrinocheilus pennocki</i>	2	1976	24778	53	1.63	20.4	X
Pangasiidae	<i>Helicophagus waandersii</i>	2	1925	26703	57	1.58	22.0	
Palaeomonidae	<i>Macrobrachium sp.</i>	9	1854	28557	61	1.52	23.5	X
Cyprinidae	<i>Hypsibarbus malcolmi</i>	2	1798	30354	65	1.48	25.0	X
Cynoglossidae	<i>Cynoglossus microlepis</i>	2	1606	31960	68	1.32	26.3	X
Cyprinidae	<i>Cyclocheilichthys enoplos</i>	3	1346	33306	71	1.11	27.4	
Cyprinidae	<i>Luciosoma bleekeri</i>	3	1281	34587	74	1.05	28.4	
Pangasiidae	<i>Pangasius kunyit</i>	2	1149	35736	76	0.94	29.4	
Pangasiidae	<i>Pangasius macronema</i>	2	977	36713	78	0.80	30.2	
Cobitidae	<i>Botia helodes</i>	3	849	37562	80	0.70	30.9	X
Cyprinidae	<i>Puntioplites proctoysron</i>	3	780	38342	82	0.64	31.5	
Pangasiidae	<i>Pangasius polyuranodon</i>	2	725	39068	83	0.60	32.1	
Pangasiidae	<i>Pangasius larnaudii</i>	2	697	39765	85	0.57	32.7	
Pangasiidae	<i>Pangasius krempfi</i>	2	596	40361	86	0.49	33.2	
Cyprinidae	<i>Cirrhinus microlepis</i>	3	503	40864	87	0.41	33.6	
Cyprinidae	<i>Hypsibarbus lagleri</i>	2	460	41323	88	0.38	34.0	
Pangasiidae	<i>Pangasianodon hypophthalmus</i>	2	451	41774	89	0.37	34.4	
Cobitidae	<i>Botia modesta</i>	3	449	42223	90	0.37	34.7	
Cyprinidae	<i>Labiobarbus siamensis</i>	3	421	42643	91	0.35	35.1	
Cyprinidae	<i>Mekongina erythrospila</i>	2	401	43045	92	0.33	35.4	
Pangasiidae	<i>Pangasius bocourti</i>	2	399	43443	93	0.33	35.7	
Sisoridae	<i>Bagarius suchus</i>	2	369	43812	94	0.30	36.0	
Cyprinidae	<i>Probarbus jullieni</i>	2	330	44143	94	0.27	36.3	X
Cyprinidae	<i>Hypsibarbus wetmorei</i>	2	329	44471	95	0.27	36.6	
Cyprinidae	<i>Cyclocheilichthys furcatus</i>	2	309	44781	96	0.25	36.8	
Schilbeidae	<i>Clupisoma sinensis</i>	2	298	45078	96	0.24	37.1	
Cyprinidae	<i>Bangana behri</i>	2	286	45365	97	0.24	37.3	
Cyprinidae	<i>Amblyrhynchichthys truncatus</i>	3	213	45577	97	0.17	37.5	
Cyprinidae	<i>Bangana sp.</i>	2	194	45771	98	0.16	37.6	
Pangasiidae	<i>Pangasius micronemus</i>	2	139	45911	98	0.11	37.8	
Cyprinidae	<i>Probarbus labeamajor</i>	2	121	46032	98	0.10	37.9	
Dasyatidae	<i>Dasyatis laosensis</i>	2	116	46149	99	0.10	37.9	
Pangasiidae	<i>Pangasius pleurotaenia</i>	2	116	46265	99	0.10	38.0	

Family	Scientific Name	Guild	Guilds 2,3,8,9			All Guilds (121607 kg)		Model species
			Total Weight (kg)	Cumulative weight (kg)	Cumulative (%)	% of total catch	Cumulative %	
Cobitidae	<i>Botia sp. cf. lecontei</i>	2	99	46364	99	0.08	38.1	
Soleidae	<i>Brachirus harmandi</i>	2	68	46432	99	0.06	38.2	
Pangasiidae	<i>Pangasius pangasius</i>	2	58	46491	99	0.05	38.2	
Cyprinidae	<i>Garra fasciacauda</i>	2	56	46547	99	0.05	38.3	
Pangasiidae	<i>Pangasius siamensis</i>	2	51	46598	100	0.04	38.3	
Clupeidae	<i>Tenualosa thibaudeaui</i>	8	41	46639	100	0.03	38.4	
Engraulidae	<i>Lycotrhissa crocodilus</i>	8	35	46674	100	0.03	38.4	
Cyprinidae	<i>Cirrhinus prosemion</i>	3	31	46705	100	0.03	38.4	
Pangasiidae	<i>Pangasius spp.</i>	2	23	46728	100	0.02	38.4	
Siluridae	<i>Kryptopterus bicirrhis</i>	2	15	46743	100	0.01	38.4	
Pangasiidae	<i>Pangasianodon gigas</i>	2	13	46756	100	0.01	38.4	X
Cyprinidae	<i>Osteochilus waandersii</i>	2	10	46766	100	0.01	38.5	
Megalopidae	<i>Megalops cyprinoides</i>	9	9	46775	100	0.01	38.5	
Cyprinidae	<i>Puntiplites bulu</i>	2	8	46782	100	0.01	38.5	
Cobitidae	<i>Botia sp. cf. beauforti</i>	2	6	46789	100	0.01	38.5	
Clupeidae	<i>Tenualosa toli</i>	8	4	46793	100	0.00	38.5	
Anguillidae	<i>Anguilla marmorata</i>	9	2	46796	100	0.00	38.5	
Cyprinidae	<i>Cirrhinus molitorella</i>	3	2	46798	100	0.00	38.5	
Cyprinidae	<i>Puntiplites waandersi</i>	2	1	46799	100	0.00	38.5	
Cyprinidae	<i>Aptosyax grypus</i>	2	0	46800	100	0.00	38.5	

Appendix 2. Spawning period estimation

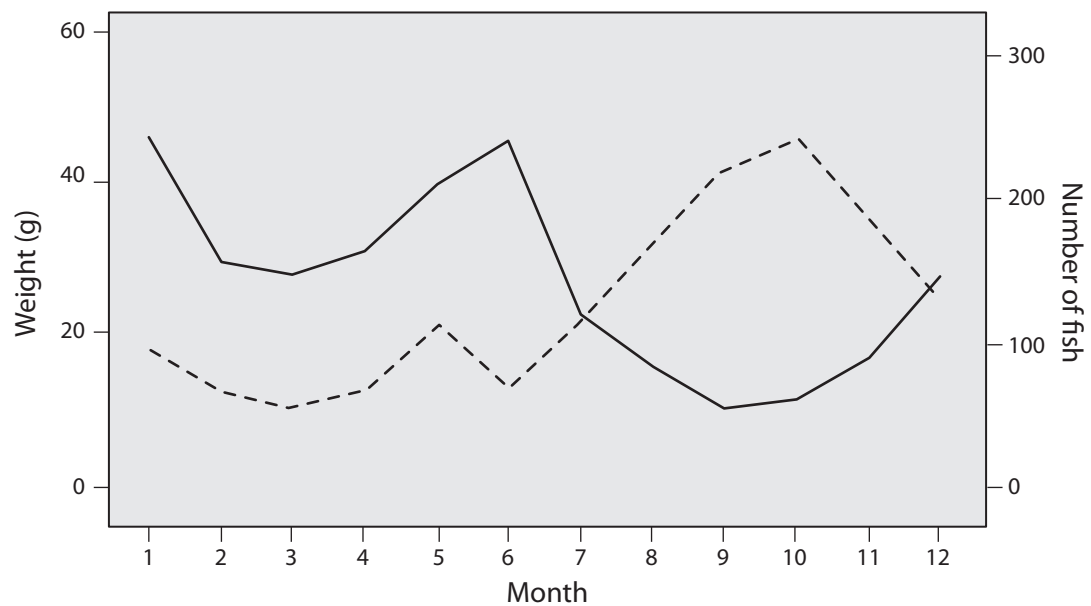


Figure A2.1 *Cynoglossus microlepis* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

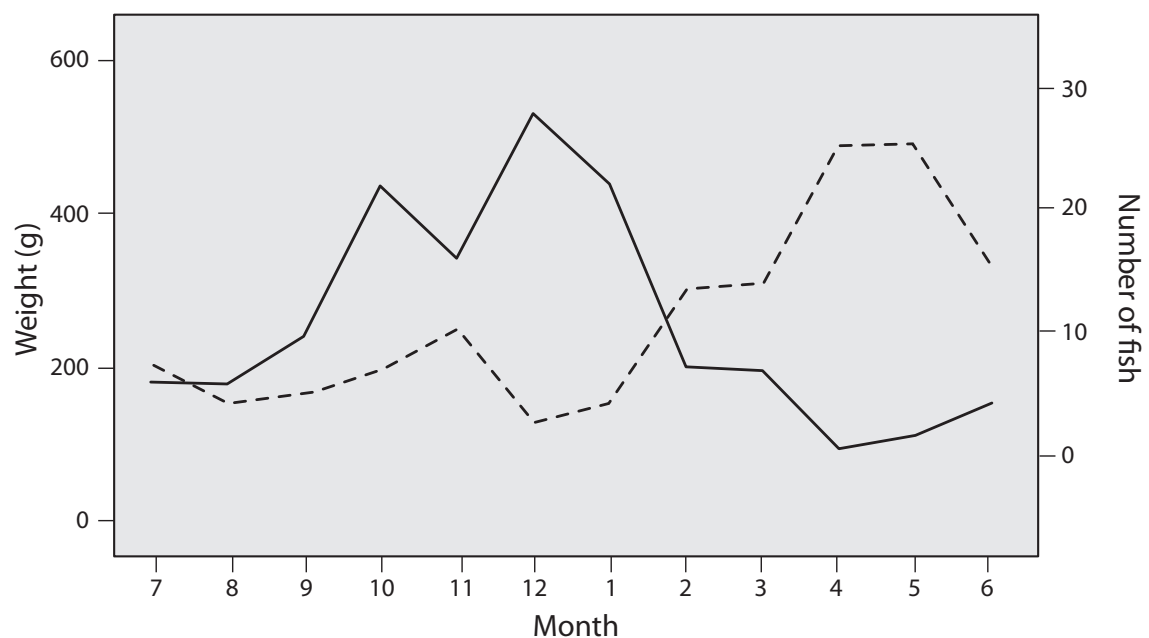


Figure A2.2 *Hypsibarbus malcolmi* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

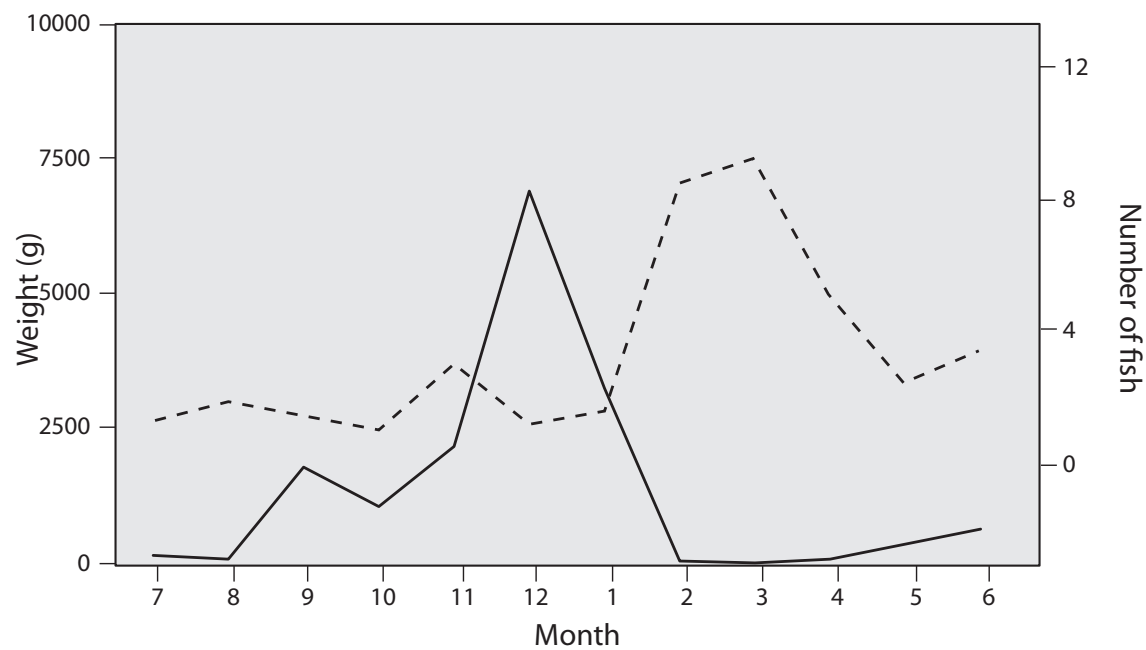


Figure A2.3 *Probarbus jullieni* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

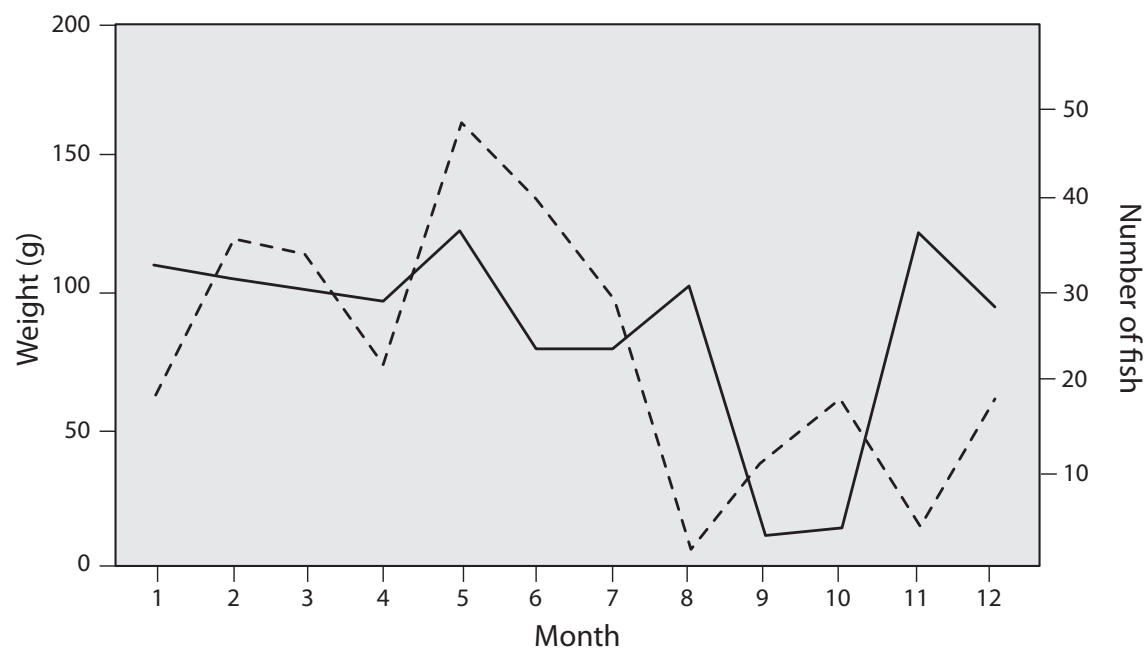


Figure A2.4 *Gyrinocheilus pennocki* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

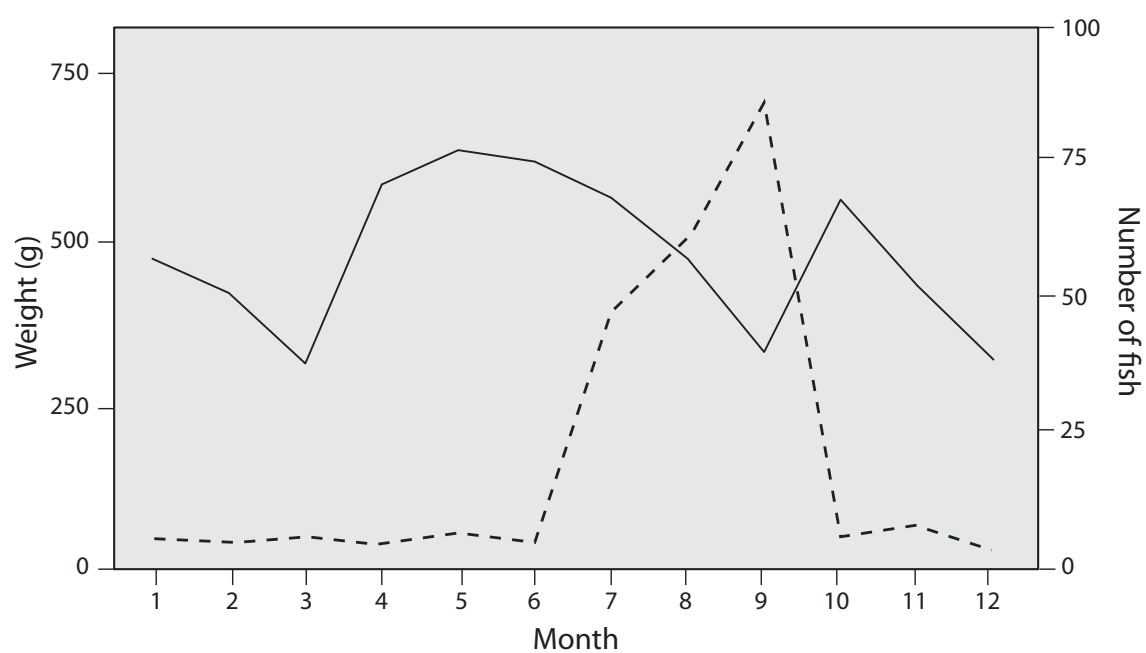


Figure A2.5 *Pangasius conchophilus* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

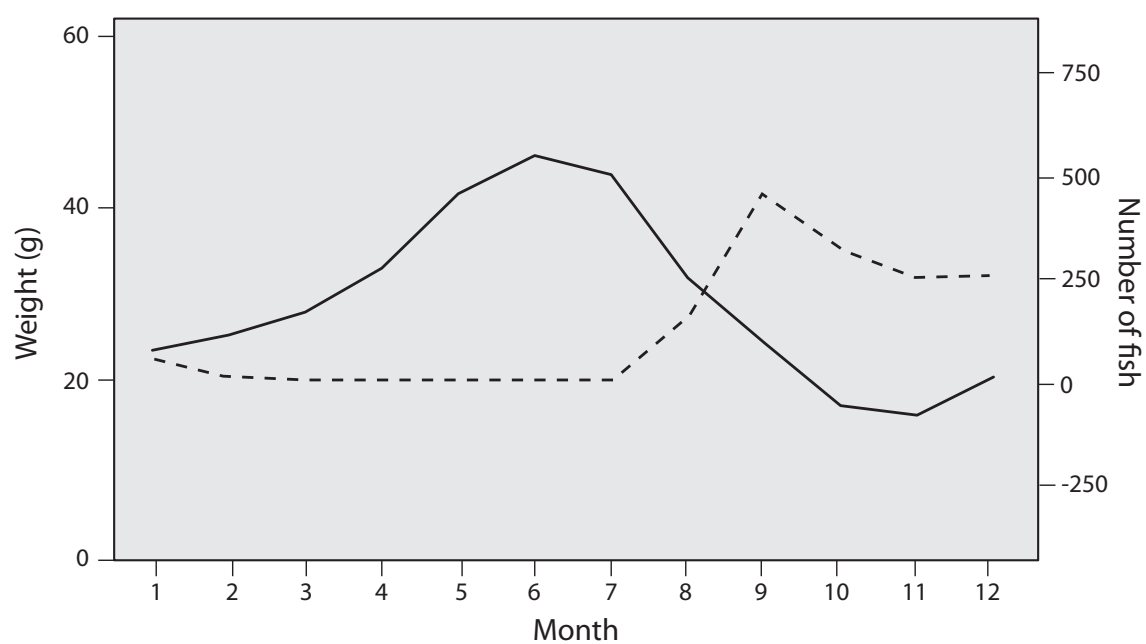


Figure A2.6 *Botia helodes* mean weight (solid line) and mean number of fish caught per fisher per day (broken line).

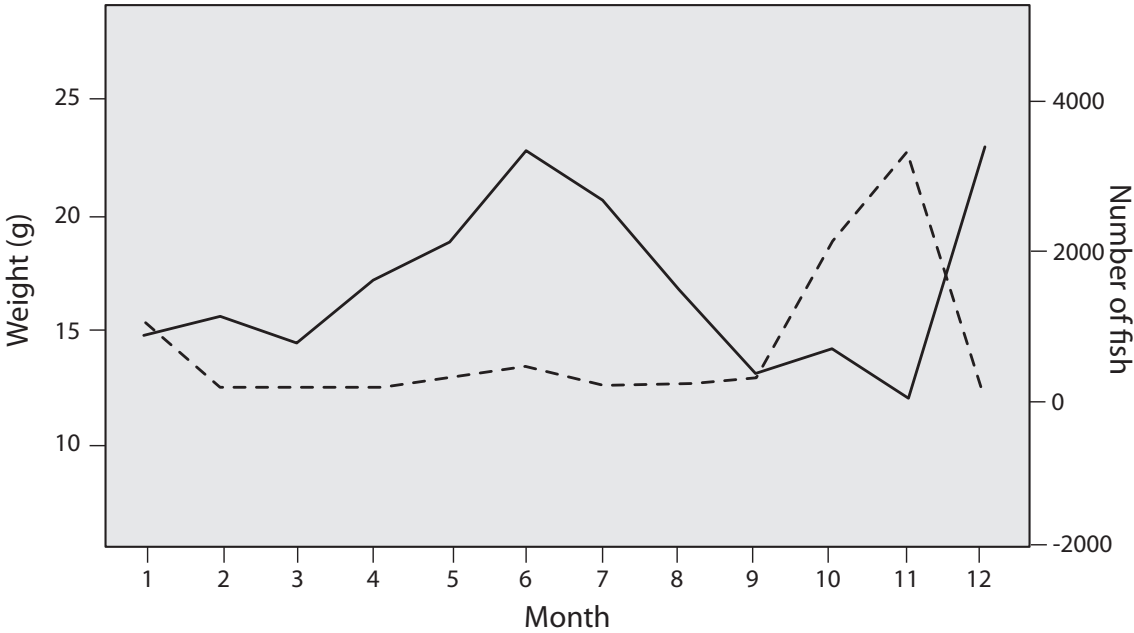


Figure A2.7 *Henichorynchus lobatus* mean weight (solid line) and mean number of fish caught per day (broken line). Filter: $\bar{W} < 100\text{g}$.

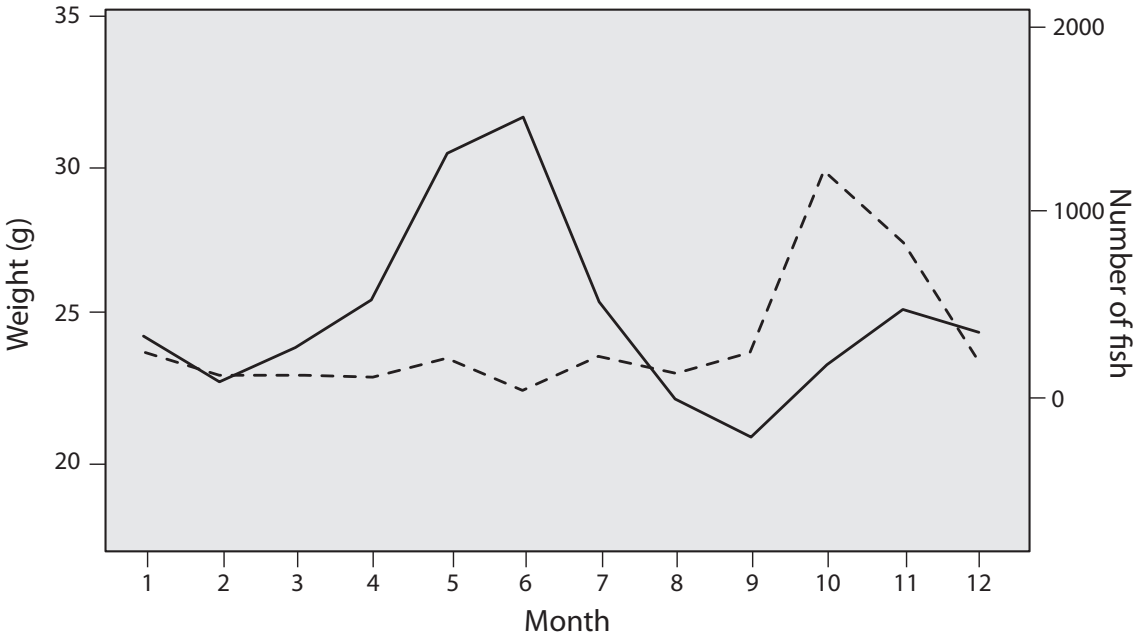


Figure A2.8 *Henichorynchus siamensis* mean weight (solid line) and mean number of fish caught per day (broken line). Filter: $\bar{W} < 100\text{g}$.

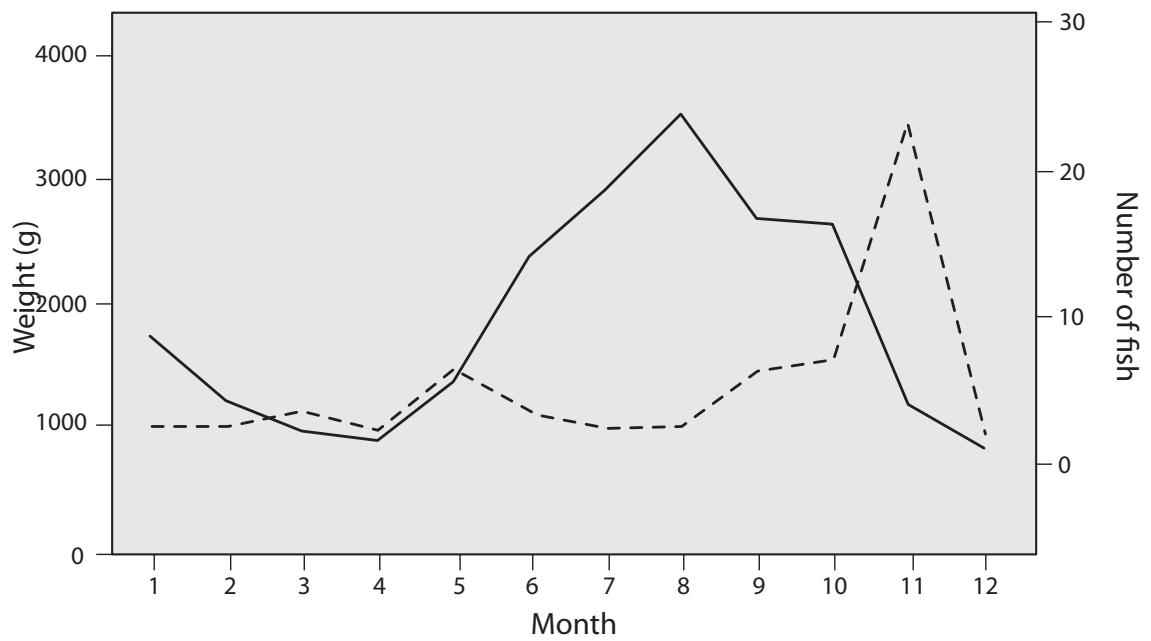


Figure A2.9 *Cosmochilus harmandii* weight (solid line) and mean number of fish caught per day (broken line).

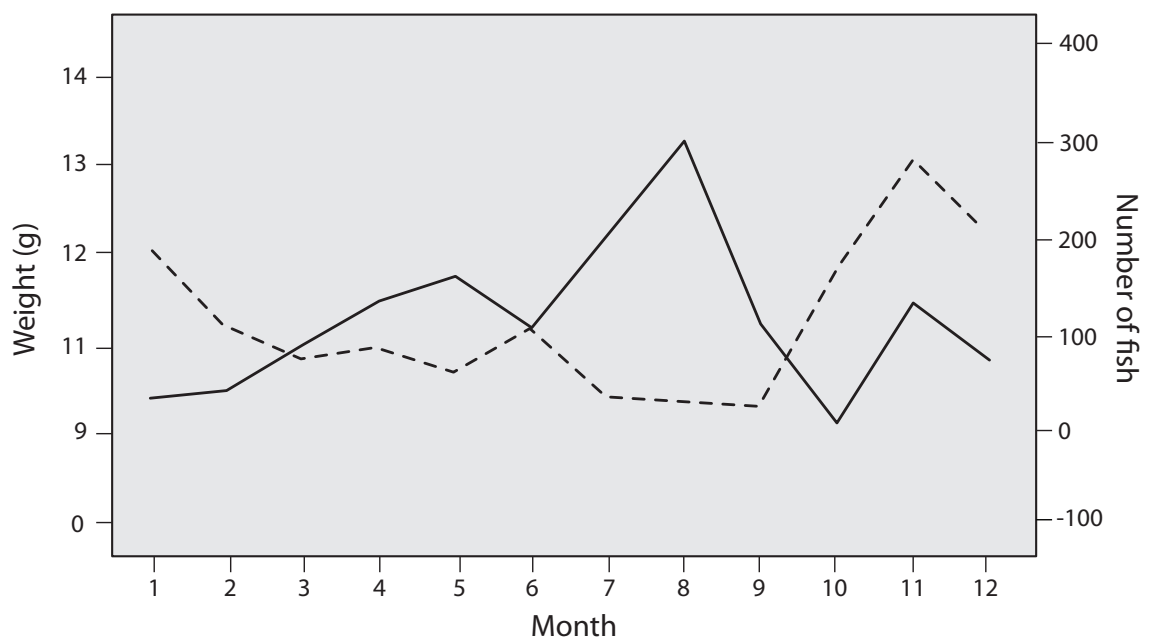


Figure A2.10 *Paralabuca typus* mean weight (solid line) and mean number of fish caught per day (broken line). Filter: $\bar{W} < 20\text{g}$.

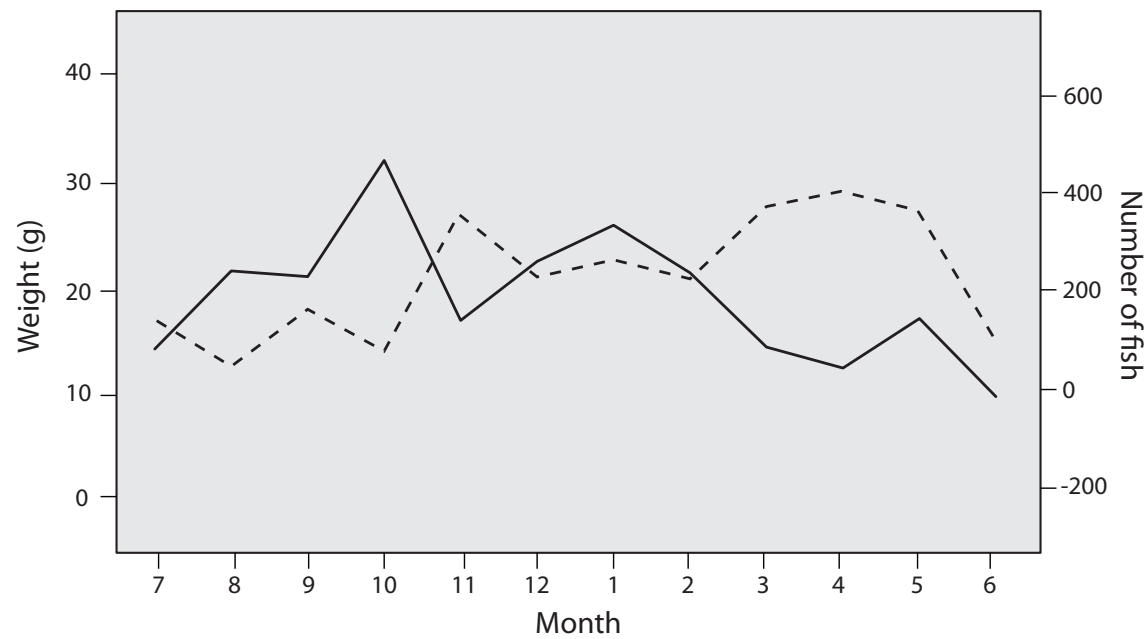
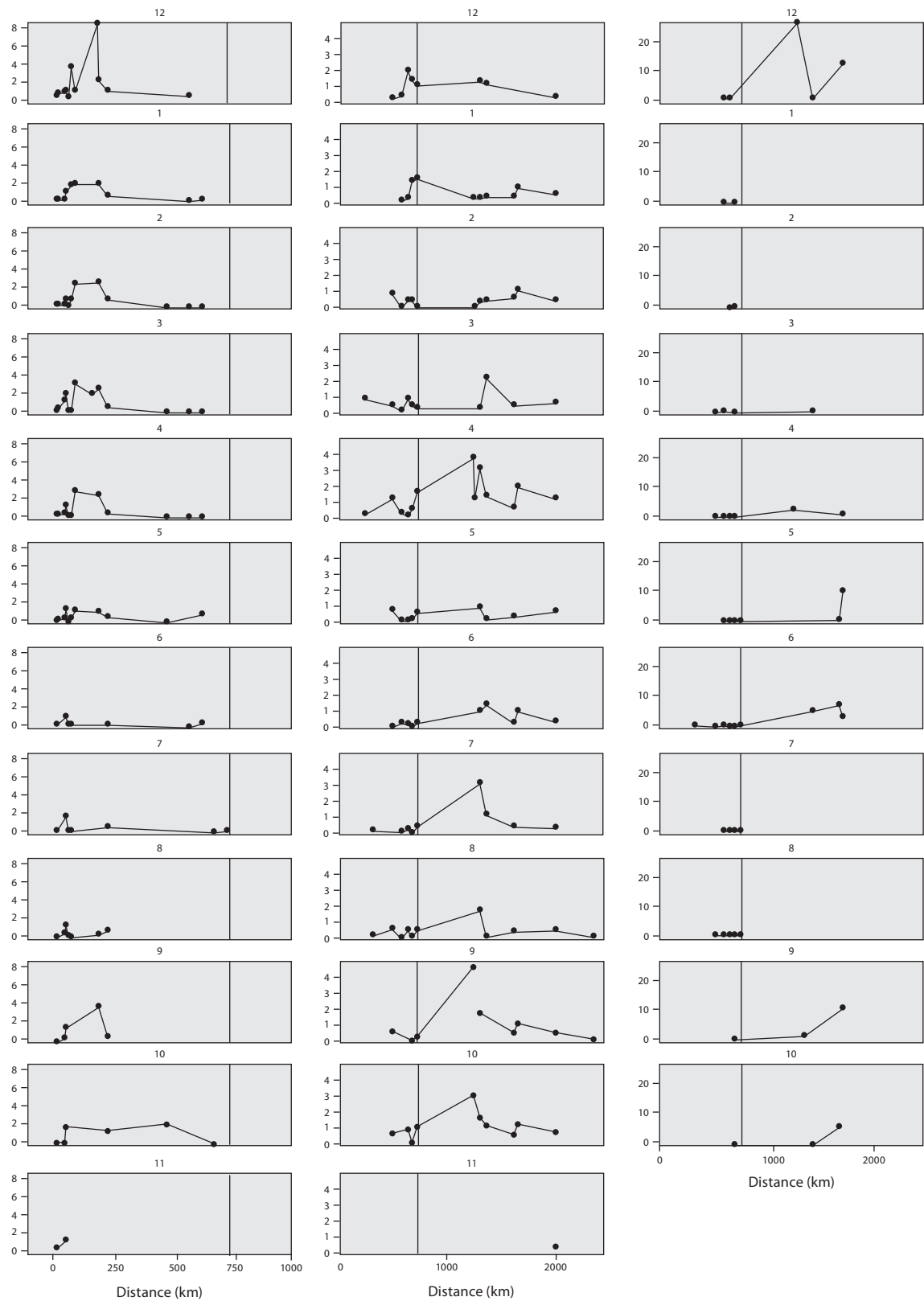
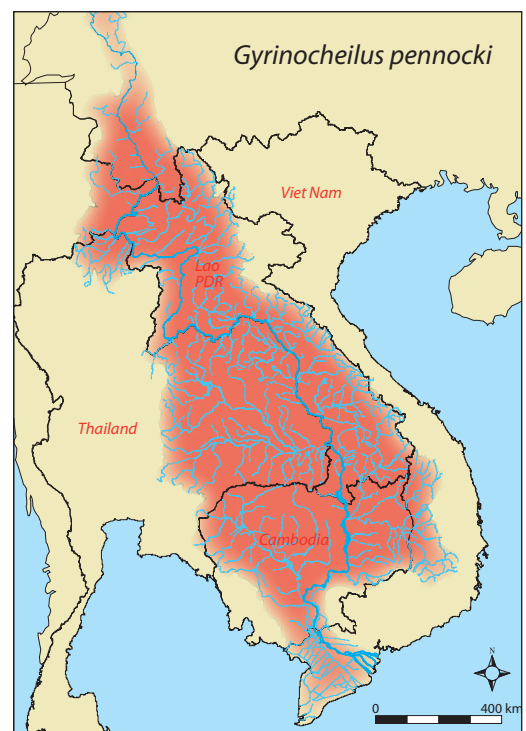
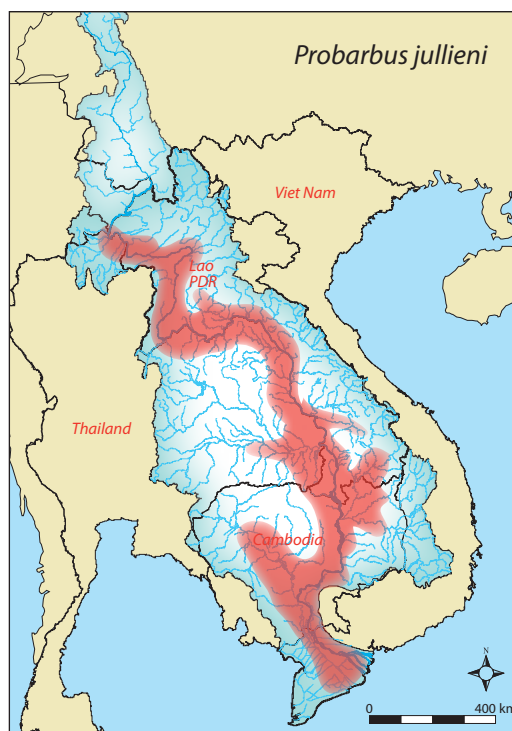
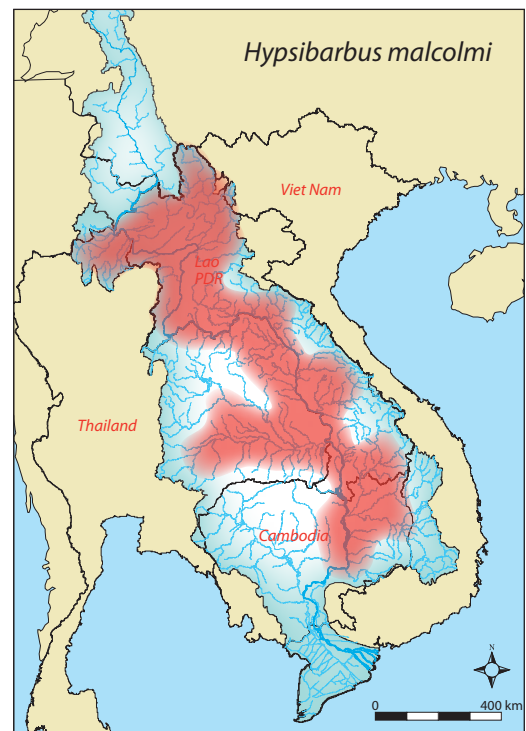
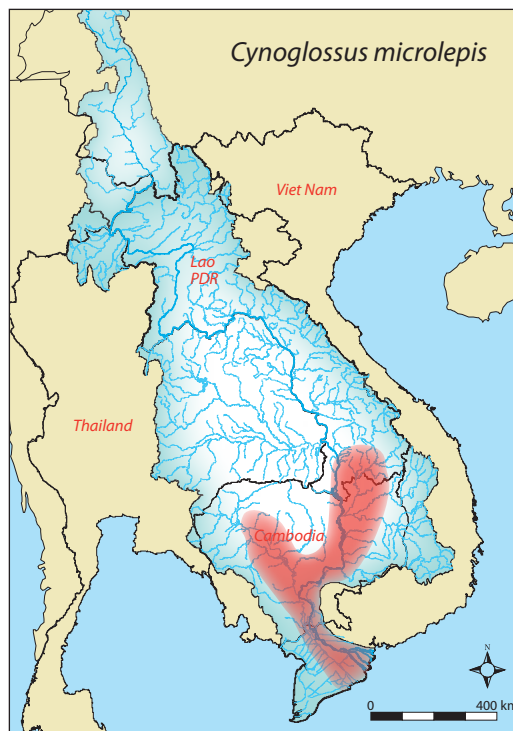


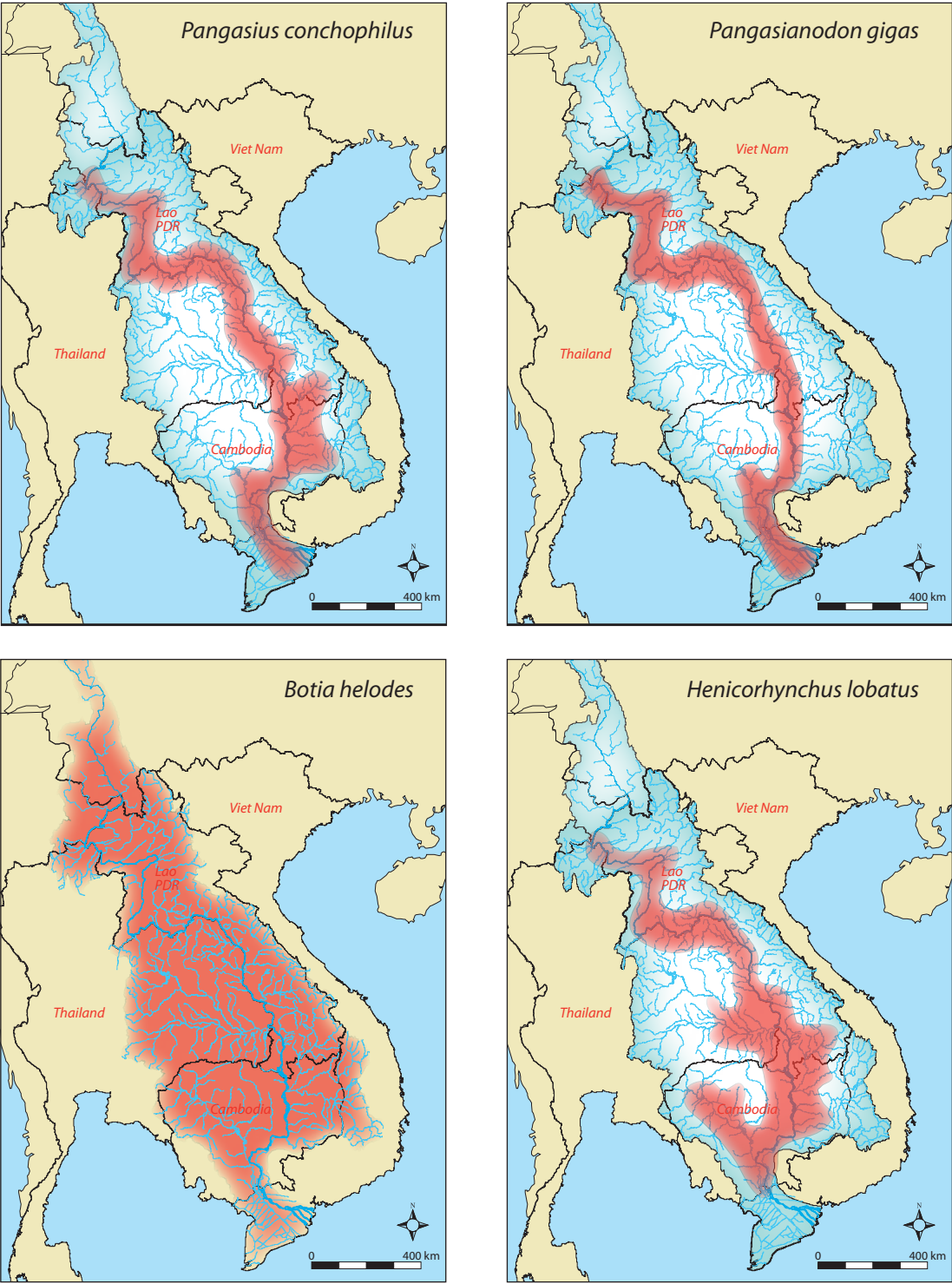
Figure A2.11 *Macrobrachium* spp. mean weight (solid line) and mean number of fish caught per day (broken line)

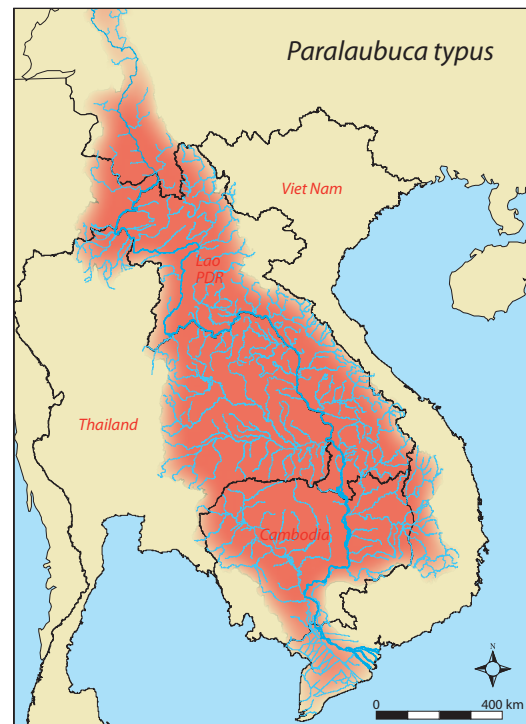
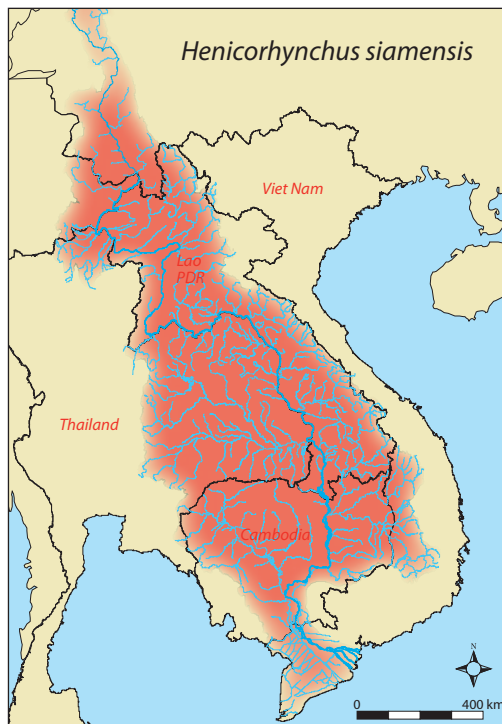
Appendix 3. Habitat distribution estimation



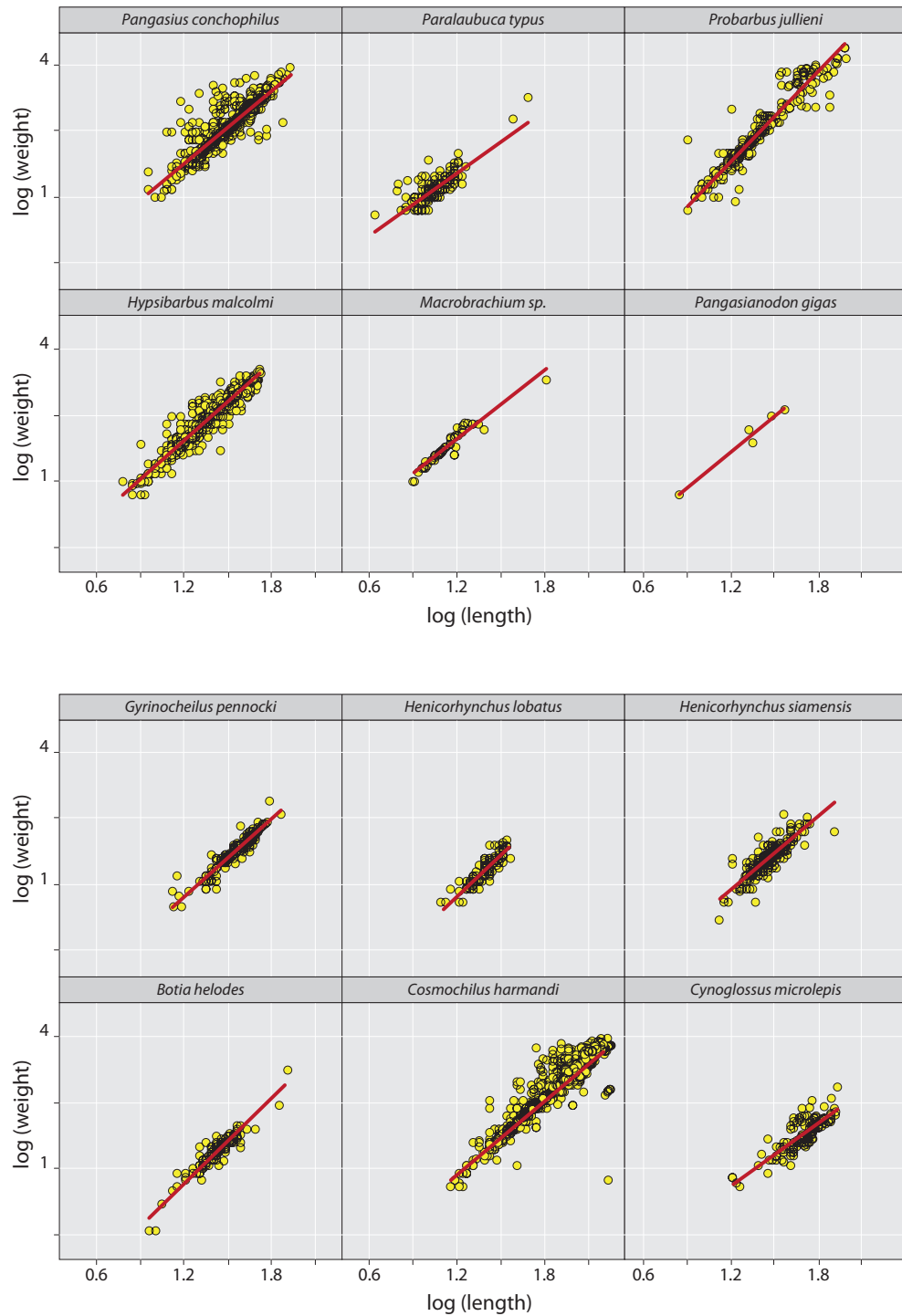
Appendix 4. Model species occurrence maps







Appendix 5. Weight-length data with fitted regression models



Appendix 6. Tabular values of lamda for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

Table A6.1 Tabular values of λ for *Henicorhynchus lobatus* and *Henicorhynchus siamensis* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

		<i>Henicorhynchus lobatus</i> High										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.46	0.57	0.7	0.83	0.96	1.1	1.23	1.36	1.5	1.63	
	0.90	0.45	0.56	0.68	0.8	0.93	1.06	1.18	1.31	1.44	1.57	
	0.80	0.44	0.55	0.66	0.78	0.9	1.02	1.14	1.26	1.38	1.5	
	0.70	0.44	0.54	0.64	0.75	0.86	0.98	1.09	1.21	1.32	1.44	
	0.60	0.43	0.52	0.62	0.73	0.83	0.94	1.05	1.16	1.27	1.38	
avoiding turbine passage	0.50	0.43	0.51	0.6	0.7	0.8	0.9	1.11	1.21	1.31		
	0.40	0.42	0.5	0.58	0.67	0.77	0.86	0.96	1.06	1.15	1.25	
	0.30	0.41	0.48	0.56	0.65	0.73	0.82	0.91	1	1.1	1.19	
	0.20	0.41	0.47	0.54	0.62	0.7	0.79	0.87	0.95	1.04	1.12	
	0.10	0.4	0.46	0.52	0.59	0.67	0.75	0.82	0.9	0.98	1.06	

		<i>Henicorhynchus siamensis</i> High										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.59	0.71	0.83	0.95	1.07	1.19	1.3	1.41	1.53	1.64	
	0.90	0.58	0.71	0.82	0.94	1.05	1.16	1.27	1.38	1.49	1.6	
	0.80	0.58	0.7	0.81	0.92	1.03	1.14	1.25	1.35	1.46	1.56	
	0.70	0.57	0.69	0.8	0.91	1.01	1.12	1.22	1.32	1.42	1.52	
	0.60	0.57	0.68	0.79	0.89	0.99	1.09	1.19	1.29	1.39	1.49	
avoiding turbine passage	0.50	0.57	0.67	0.78	0.88	0.98	1.07	1.17	1.26	1.36	1.45	
	0.40	0.56	0.67	0.77	0.86	0.96	1.05	1.14	1.23	1.32	1.41	
	0.30	0.56	0.66	0.75	0.85	0.94	1.03	1.12	1.2	1.29	1.38	
	0.20	0.55	0.65	0.74	0.83	0.92	1.01	1.09	1.18	1.26	1.34	
	0.10	0.55	0.64	0.73	0.82	0.9	0.99	1.07	1.15	1.23	1.31	

		<i>Henicorhynchus lobatus</i> Medium										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.42	0.5	0.57	0.66	0.74	0.83	0.92	1.01	1.1	1.18	
	0.90	0.42	0.48	0.56	0.64	0.72	0.8	0.88	0.96	1.05	1.13	
	0.80	0.41	0.47	0.54	0.61	0.69	0.77	0.84	0.92	1	1.08	
	0.70	0.41	0.46	0.53	0.59	0.66	0.73	0.81	0.88	0.95	1.03	
	0.60	0.4	0.45	0.51	0.57	0.64	0.7	0.77	0.84	0.91	0.97	
avoiding turbine passage	0.50	0.4	0.44	0.49	0.55	0.61	0.67	0.73	0.79	0.86	0.92	
	0.40	0.39	0.43	0.48	0.53	0.58	0.64	0.69	0.75	0.81	0.87	
	0.30	0.39	0.42	0.46	0.51	0.55	0.61	0.66	0.71	0.76	0.82	
	0.20	0.38	0.41	0.44	0.48	0.53	0.57	0.62	0.67	0.72	0.77	
	0.10	0.37	0.4	0.43	0.46	0.5	0.54	0.58	0.63	0.67	0.72	

		<i>Henicorhynchus siamensis</i> Medium										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.53	0.61	0.69	0.76	0.83	0.91	0.98	1.05	1.12	1.19	
	0.90	0.53	0.6	0.68	0.75	0.82	0.88	0.95	1.02	1.08	1.15	
	0.80	0.53	0.6	0.66	0.73	0.8	0.86	0.92	0.99	1.05	1.11	
	0.70	0.52	0.59	0.65	0.72	0.78	0.84	0.9	0.96	1.01	1.07	
	0.60	0.52	0.58	0.64	0.7	0.76	0.81	0.87	0.93	0.98	1.04	
avoiding turbine passage	0.50	0.51	0.57	0.63	0.68	0.74	0.79	0.84	0.9	0.95	1	
	0.40	0.51	0.56	0.62	0.67	0.72	0.77	0.82	0.87	0.92	0.96	
	0.30	0.5	0.56	0.61	0.65	0.7	0.75	0.79	0.84	0.88	0.93	
	0.20	0.5	0.55	0.59	0.64	0.68	0.73	0.77	0.81	0.85	0.89	
	0.10	0.5	0.54	0.58	0.62	0.67	0.71	0.75	0.78	0.82	0.86	

		<i>Henicorhynchus lobatus</i> Low										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.41	0.48	0.54	0.62	0.69	0.77	0.84	0.92	1	1.07	
	0.90	0.41	0.47	0.53	0.6	0.66	0.73	0.81	0.88	0.95	1.02	
	0.80	0.4	0.46	0.51	0.57	0.64	0.7	0.77	0.84	0.9	0.97	
	0.70	0.4	0.44	0.5	0.55	0.61	0.67	0.73	0.8	0.86	0.92	
	0.60	0.39	0.43	0.48	0.53	0.59	0.64	0.7	0.76	0.82	0.87	
avoiding turbine passage	0.50	0.39	0.42	0.47	0.51	0.56	0.61	0.66	0.72	0.77	0.82	
	0.40	0.38	0.41	0.45	0.49	0.54	0.59	0.63	0.68	0.73	0.78	
	0.30	0.38	0.4	0.43	0.47	0.51	0.55	0.59	0.64	0.68	0.73	
	0.20	0.37	0.39	0.42	0.45	0.48	0.52	0.56	0.6	0.64	0.68	
	0.10	0.37	0.38	0.4	0.43	0.46	0.49	0.52	0.56	0.59	0.63	

		<i>Henicorhynchus siamensis</i> Low										
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.53	0.6	0.66	0.73	0.79	0.86	0.92	0.98	1.05	1.11	
	0.90	0.52	0.59	0.65	0.71	0.77	0.84	0.89	0.95	1.01	1.07	
	0.80	0.52	0.58	0.64	0.7	0.76	0.81	0.87	0.92	0.98	1.03	
	0.70	0.51	0.57	0.63	0.68	0.74	0.79	0.84	0.89	0.94	1	
	0.60	0.51	0.56	0.62	0.67	0.72	0.77	0.82	0.86	0.91	0.96	
avoiding turbine passage	0.50	0.5	0.55	0.6	0.65	0.7	0.74	0.79	0.83	0.88	0.92	
	0.40	0.5	0.55	0.59	0.64	0.68	0.72	0.76	0.81	0.85	0.89	
	0.30	0.5	0.54	0.58	0.62	0.66	0.7	0.74	0.78	0.82	0.85	
	0.20	0.49	0.53	0.57	0.61	0.64	0.68	0.71	0.75	0.78	0.82	
	0.10	0.49	0.52	0.56	0.59	0.62	0.66	0.69	0.72	0.75	0.79	

Table A6.2 Tabular values of λ for *Paralabuca typus* and *Gyrinocheilus pennocki* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

Paralabuca typus High												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.98	0.69	0.81	0.94	1.06	1.18	1.3	1.43	1.55	1.67	
	0.90	0.95	0.68	0.8	0.92	1.04	1.16	1.28	1.4	1.52	1.63	
	0.80	0.95	0.67	0.79	0.91	1.03	1.14	1.25	1.37	1.49	1.6	
	0.70	0.95	0.67	0.78	0.9	1.01	1.12	1.23	1.35	1.46	1.57	
	0.60	0.95	0.68	0.77	0.88	0.99	1.1	1.21	1.32	1.43	1.53	
	0.50	0.94	0.65	0.76	0.87	0.98	1.08	1.19	1.29	1.4	1.5	
	0.40	0.94	0.64	0.75	0.86	0.96	1.06	1.17	1.27	1.37	1.47	
	0.30	0.94	0.64	0.74	0.84	0.94	1.04	1.14	1.24	1.34	1.44	
	0.20	0.93	0.63	0.73	0.83	0.93	1.03	1.12	1.22	1.31	1.41	
	0.10	0.93	0.62	0.72	0.82	0.91	1.01	1.1	1.19	1.28	1.38	

Gyrinocheilus pennocki High												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.7	0.83	0.96	1.07	1.17	1.27	1.37	1.47	1.58	1.65	
	0.90	0.7	0.83	0.94	1.05	1.15	1.25	1.35	1.44	1.53	1.61	
	0.80	0.69	0.81	0.92	1.02	1.12	1.21	1.3	1.38	1.46	1.54	
	0.70	0.69	0.81	0.92	1.02	1.12	1.21	1.3	1.38	1.46	1.54	
	0.60	0.68	0.8	0.91	1.01	1.1	1.19	1.27	1.35	1.43	1.51	
	0.50	0.68	0.8	0.9	0.99	1.08	1.17	1.25	1.32	1.4	1.47	
	0.40	0.67	0.79	0.89	0.98	1.06	1.15	1.22	1.3	1.37	1.44	
	0.30	0.67	0.78	0.88	0.97	1.05	1.13	1.2	1.27	1.34	1.41	
	0.20	0.67	0.77	0.87	0.95	1.03	1.11	1.18	1.24	1.31	1.37	
	0.10	0.66	0.76	0.86	0.94	1.01	1.09	1.16	1.22	1.28	1.34	

Paralabuca typus Medium												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.52	0.6	0.69	0.77	0.86	0.94	1.02	1.1	1.18	1.26	
0.90	0.52	0.6	0.68	0.76	0.84	0.92	1	1.07	1.15	1.23		
0.80	0.52	0.59	0.67	0.74	0.82	0.9	0.97	1.05	1.12	1.2		
0.70	0.51	0.58	0.66	0.73	0.8	0.88	0.95	1.02	1.09	1.16		
0.60	0.51	0.57	0.64	0.72	0.79	0.86	0.93	1	1.06	1.13		
0.50	0.5	0.57	0.63	0.7	0.77	0.84	0.9	0.97	1.04	1.1		
0.40	0.5	0.56	0.62	0.69	0.75	0.82	0.88	0.94	1.01	1.07		
0.30	0.49	0.55	0.61	0.67	0.74	0.8	0.86	0.92	0.98	1.04		
0.20	0.49	0.54	0.6	0.66	0.72	0.78	0.84	0.89	0.95	1.01		
0.10	0.49	0.54	0.59	0.65	0.7	0.76	0.82	0.87	0.92	0.98		

Gyrinocheilus pennocki Medium												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.66	0.77	0.86	0.95	1.03	1.11	1.19	1.26	1.33	1.4	
	0.90	0.66	0.76	0.85	0.93	1.01	1.09	1.16	1.23	1.3	1.37	
	0.80	0.65	0.75	0.84	0.92	0.99	1.07	1.13	1.2	1.27	1.33	
	0.70	0.65	0.74	0.82	0.9	0.97	1.04	1.11	1.17	1.24	1.3	
	0.60	0.64	0.73	0.81	0.89	0.96	1.02	1.09	1.15	1.21	1.28	
	0.50	0.64	0.72	0.8	0.87	0.94	1	1.06	1.12	1.17	1.23	
	0.40	0.63	0.72	0.79	0.86	0.92	0.98	1.04	1.09	1.14	1.19	
	0.30	0.63	0.71	0.78	0.84	0.9	0.96	1.01	1.07	1.12	1.16	
	0.20	0.62	0.7	0.77	0.83	0.89	0.94	0.99	1.04	1.09	1.13	
	0.10	0.62	0.69	0.76	0.82	0.87	0.92	0.97	1.02	1.06	1.1	

Paralabuca typus Low												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.51	0.57	0.63	0.7	0.77	0.83	0.9	0.96	1.03	1.09	
0.90	0.5	0.56	0.62	0.69	0.75	0.81	0.87	0.93	1	1.06		
0.80	0.5	0.55	0.61	0.67	0.73	0.79	0.85	0.91	0.97	1.02		
0.70	0.49	0.55	0.6	0.66	0.71	0.77	0.82	0.88	0.94	0.99		
0.60	0.49	0.54	0.59	0.64	0.7	0.75	0.8	0.85	0.91	0.96		
0.50	0.49	0.53	0.58	0.63	0.68	0.73	0.78	0.83	0.88	0.93		
0.40	0.48	0.52	0.57	0.61	0.66	0.71	0.76	0.8	0.85	0.89		
0.30	0.48	0.51	0.56	0.6	0.65	0.69	0.73	0.78	0.82	0.86		
0.20	0.47	0.51	0.55	0.59	0.63	0.67	0.71	0.75	0.79	0.83		
0.10	0.47	0.5	0.53	0.57	0.61	0.65	0.69	0.73	0.77	0.8		

Gyrinocheilus pennocki Low												
		Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage	1.00	0.62	0.69	0.76	0.82	0.88	0.93	0.99	1.04	1.09	1.14	
	0.90	0.61	0.68	0.74	0.8	0.86	0.91	0.96	1.01	1.05	1.1	
	0.80	0.61	0.67	0.73	0.79	0.84	0.89	0.93	0.98	1.02	1.06	
	0.70	0.6	0.66	0.72	0.77	0.82	0.86	0.91	0.95	0.99	1.03	
	0.60	0.6	0.66	0.71	0.76	0.8	0.84	0.88	0.92	0.96	1	
	0.50	0.59	0.65	0.69	0.74	0.78	0.82	0.86	0.89	0.93	0.96	
	0.40	0.58	0.64	0.68	0.72	0.76	0.8	0.84	0.87	0.91	0.94	
	0.30	0.58	0.63	0.67	0.71	0.75	0.78	0.81	0.84	0.87	0.9	
	0.20	0.58	0.62	0.66	0.7	0.73	0.76	0.79	0.82	0.85	0.87	
	0.10	0.58	0.61	0.65	0.68	0.71	0.74	0.77	0.79	0.82	0.84	

Table A6.3 Tabular values of λ for *Botia helodes* and *Hypsibarbus malcolmi* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

Botia helodes High												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
	1.00	0.68	0.8	0.91	1.02	1.12	1.22	1.32	1.41	1.51	1.6	
	0.90	0.68	0.79	0.9	1	1.09	1.19	1.28	1.38	1.47	1.56	
	0.80	0.67	0.78	0.88	0.98	1.07	1.16	1.25	1.34	1.43	1.51	
	0.70	0.67	0.77	0.87	0.96	1.05	1.14	1.22	1.31	1.39	1.47	
	0.60	0.66	0.76	0.85	0.94	1.03	1.11	1.19	1.27	1.35	1.43	
	0.50	0.66	0.75	0.84	0.93	1.01	1.08	1.16	1.24	1.31	1.38	
	0.40	0.65	0.74	0.83	0.91	0.98	1.06	1.13	1.2	1.27	1.34	
	0.30	0.65	0.73	0.81	0.89	0.96	1.03	1.1	1.17	1.23	1.3	
	0.20	0.64	0.73	0.8	0.87	0.94	1.01	1.07	1.14	1.2	1.26	
	0.10	0.64	0.72	0.79	0.86	0.92	0.98	1.04	1.1	1.16	1.22	

Hypsibarbus malcolmi High												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
1.00	0.77	0.84	0.89	0.93	0.98	1.01	1.05	1.08	1.12	1.15		
0.90	0.77	0.83	0.87	0.91	0.95	0.99	1.02	1.05	1.08	1.10		
0.80	0.76	0.81	0.86	0.90	0.93	0.96	0.99	1.04	1.08	1.10		
0.70	0.76	0.80	0.84	0.88	0.91	0.93	0.96	0.99	1.00	1.03		
0.60	0.75	0.79	0.83	0.86	0.88	0.9	0.92	0.95	0.97	1.00		
0.50	0.75	0.78	0.82	0.84	0.86	0.88	0.9	0.93	0.93	0.95		
0.40	0.74	0.77	0.80	0.82	0.84	0.86	0.88	0.89	0.90	0.91		
0.30	0.73	0.76	0.79	0.81	0.82	0.84	0.85	0.86	0.87	0.88		
0.20	0.73	0.76	0.78	0.79	0.81	0.82	0.83	0.84	0.85	0.85		
	0.10	0.72	0.75	0.76	0.78	0.79	0.80	0.81	0.82	0.83	0.83	
Botia helodes Medium												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
1.00	0.63	0.69	0.75	0.81	0.87	0.93	0.98	1.04	1.09	1.15		
0.90	0.62	0.68	0.74	0.79	0.85	0.9	0.95	1	1.05	1.1		
0.80	0.62	0.67	0.72	0.78	0.83	0.87	0.92	0.97	1.01	1.06		
0.70	0.61	0.66	0.71	0.76	0.8	0.85	0.89	0.93	0.97	1.01		
0.60	0.61	0.65	0.7	0.74	0.78	0.82	0.86	0.9	0.93	0.97		
0.50	0.61	0.65	0.69	0.73	0.77	0.81	0.83	0.86	0.9	0.93		
0.40	0.6	0.63	0.67	0.7	0.74	0.77	0.8	0.83	0.86	0.89		
0.30	0.59	0.62	0.65	0.68	0.71	0.74	0.77	0.8	0.82	0.85		
0.20	0.58	0.61	0.64	0.67	0.69	0.72	0.74	0.77	0.79	0.81		
	0.10	0.58	0.6	0.63	0.65	0.67	0.7	0.72	0.74	0.76	0.78	
Hypsibarbus malcolmi Medium												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
1.00	0.76	0.81	0.85	0.89	0.93	0.96	0.99	1.02	1.05	1.07		
0.90	0.75	0.80	0.84	0.87	0.9	0.93	0.96	0.98	1.00	1.03		
0.80	0.74	0.79	0.82	0.85	0.88	0.9	0.92	0.95	0.97	0.98		
0.70	0.74	0.78	0.81	0.83	0.86	0.88	0.89	0.91	0.93	0.94		
0.60	0.73	0.77	0.79	0.81	0.83	0.85	0.87	0.88	0.89	0.91		
0.50	0.73	0.76	0.78	0.8	0.82	0.84	0.85	0.86	0.87	0.88		
0.40	0.72	0.74	0.76	0.77	0.79	0.80	0.81	0.82	0.83	0.84		
0.30	0.72	0.73	0.75	0.76	0.77	0.78	0.79	0.80	0.80	0.81		
0.20	0.71	0.72	0.74	0.74	0.75	0.76	0.77	0.77	0.78	0.78		
	0.10	0.70	0.72	0.72	0.73	0.73	0.74	0.74	0.75	0.75	0.75	
Botia helodes Low												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
1.00	0.62	0.68	0.73	0.79	0.84	0.89	0.93	0.97	1.04	1.09		
0.90	0.61	0.67	0.72	0.77	0.82	0.86	0.91	0.95	1	1.04		
0.80	0.61	0.66	0.7	0.75	0.79	0.84	0.88	0.92	0.96	1		
0.70	0.6	0.65	0.69	0.73	0.77	0.81	0.85	0.88	0.92	0.95		
0.60	0.6	0.64	0.67	0.71	0.75	0.78	0.82	0.85	0.88	0.91		
0.50	0.59	0.63	0.66	0.69	0.73	0.76	0.79	0.81	0.84	0.87		
0.40	0.58	0.62	0.65	0.68	0.73	0.76	0.78	0.81	0.83			
0.30	0.58	0.6	0.63	0.64	0.68	0.7	0.72	0.73	0.75	0.76		
0.20	0.57	0.59	0.61	0.62	0.64	0.66	0.67	0.69	0.7	0.72		
	0.10	0.57	0.59	0.61	0.62	0.64	0.66	0.67	0.69	0.7	0.72	
Hypsibarbus malcolmi Low												
		Up stream passage success rate										
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
1.00	0.75	0.79	0.83	0.86	0.89	0.92	0.95	0.98	1.01	1.03		
0.90	0.74	0.78	0.82	0.85	0.88	0.9	0.92	0.94	0.97	0.99		
0.80	0.73	0.77	0.80	0.83	0.85	0.87	0.89	0.91	0.93	0.94		
0.70	0.73	0.76	0.79	0.81	0.83	0.84	0.86	0.87	0.89	0.90		
0.60	0.72	0.75	0.77	0.79	0.80	0.82	0.83	0.84	0.85	0.86		
0.50	0.72	0.74	0.76	0.77	0.78	0.79	0.80	0.81	0.82	0.83		
0.40	0.71	0.73	0.74	0.75	0.76	0.77	0.78	0.78	0.79	0.80		
0.30	0.71	0.72	0.73	0.74	0.74	0.75	0.75	0.76	0.76	0.77		
0.20	0.70 0.71	0.72	0.72	0.73	0.73	0.74	0.74	0.75	0.75			
	0.10	0.69 0.70 0.70 0.71	0.71	0.72	0.72	0.73	0.73	0.74				

Table A6.4 Tabular values of λ for *Cosmochilus harmandii* and *Pangasius conchophilus* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

Cosmochilus harmandii High												Pangasius conchophilus High															
		Up stream passage success rate												Up stream passage success rate													
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00				
		1.00	0.88	0.93	0.96	0.99	1.02	1.04	1.06	1.08	1.1	1.12			1.00	0.88	0.93	0.96	0.99	1.02	1.04	1.06	1.08	1.09	1.14		
		0.90	0.87	0.92	0.95	0.97	1.00	1.02	1.03	1.05	1.07	1.08			0.90	0.88	0.92	0.95	0.98	1.02	1.03	1.05	1.06	1.07	1.10		
		0.80	0.87	0.91	0.93	0.96	0.98	0.99	1.01	1.02	1.03	1.05			0.80	0.87	0.91	0.94	0.96	0.98	1.01	1.02	1.03	1.04	1.06	1.08	
		0.70	0.86	0.9	0.92	0.94	0.96	0.97	0.99	1.01	1.02	1.02			0.70	0.87	0.9	0.93	0.94	0.96	0.98	0.99	1.01	1.02	1.03	1.05	
		0.60	0.86	0.89	0.91	0.93	0.94	0.95	0.96	0.97	0.98	0.99			0.60	0.86	0.89	0.91	0.93	0.94	0.96	0.97	0.98	0.99	1.01	1.02	
		0.50	0.85	0.88	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97			0.50	0.85	0.88	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.99	
Proportion of mature fish avoiding turbine passage		0.40	0.84	0.87	0.88	0.9	0.91	0.92	0.92	0.93	0.94	0.94			0.40	0.85	0.87	0.89	0.9	0.92	0.92	0.93	0.94	0.95	0.95	0.96	
		0.30	0.84	0.86	0.87	0.88	0.89	0.9	0.91	0.91	0.91	0.92	0.92			0.30	0.85	0.87	0.88	0.89	0.9	0.91	0.92	0.92	0.93	0.93	0.94
		0.20	0.83	0.85	0.86	0.87	0.88	0.89	0.89	0.9	0.9	0.9	0.9			0.20	0.84	0.86	0.87	0.88	0.89	0.9	0.91	0.91	0.91	0.92	0.92
		0.10	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89			0.10	0.84	0.85	0.86	0.87	0.88	0.88	0.89	0.89	0.9	0.9	
		0.10	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89			0.10	0.84	0.85	0.86	0.87	0.88	0.88	0.89	0.89	0.9	0.9	
		0.10	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89			0.10	0.84	0.85	0.86	0.87	0.88	0.88	0.89	0.89	0.9	0.9	
		0.10	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.88	0.88	0.88	0.89			0.10	0.84	0.85	0.86	0.87	0.88	0.88	0.89	0.89	0.9	0.9	

Cosmochilus harmandii Medium												Pangasius conchophilus Medium													
		Up stream passage success rate												Up stream passage success rate											
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00		
	1.00	0.85	0.88	0.9	0.93	0.94	0.96	0.98	0.99	1.01	1.02			1.00	0.86	0.88	0.91	0.93	0.94	0.96	0.98	0.99	1.01	1.02	
	0.90	0.84	0.87	0.89	0.91	0.92	0.93	0.95	0.96	0.97	0.98			0.90	0.85	0.87	0.89	0.91	0.92	0.93	0.95	0.96	0.97	0.99	
	0.80	0.83	0.86	0.87	0.89	0.9	0.91	0.92	0.93	0.93	0.94			0.80	0.84	0.86	0.88	0.89	0.9	0.91	0.92	0.93	0.93	0.94	
	0.70	0.83	0.84	0.86	0.87	0.88	0.88	0.89	0.9	0.91	0.91			0.70	0.84	0.85	0.86	0.87	0.88	0.89	0.89	0.91	0.91	0.92	
	0.60	0.82	0.83	0.84	0.85	0.86	0.86	0.87	0.87	0.88	0.88			0.60	0.83	0.84	0.85	0.85	0.86	0.87	0.87	0.88	0.88	0.88	
	0.50	0.81	0.82	0.83	0.83	0.84	0.84	0.85	0.85	0.85	0.86			0.50	0.82	0.83	0.83	0.84	0.84	0.85	0.85	0.85	0.86	0.86	
Proportion of mature fish avoiding turbine passage		0.40	0.81	0.81	0.82	0.82	0.83	0.83	0.83	0.83	0.83	0.83			0.40	0.82	0.82	0.82	0.83	0.83	0.84	0.84	0.84	0.84	0.84
	0.30	0.8	0.8	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81			0.30	0.81	0.81	0.81	0.81	0.82	0.82	0.82	0.82	0.82	0.83	
	0.20	0.8	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79			0.20	0.8	0.8	0.8	0.8	0.8	0.81	0.81	0.81	0.81	0.81	
	0.10	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78			0.10	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8	0.8	
	0.10	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78			0.10	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8	0.8	
	0.10	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78			0.10	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8	0.8	
	0.10	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78			0.10	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8	0.8	
Cosmochilus harmandii Low												Pangasius conchophilus Low													
		Up stream passage success rate												Up stream passage success rate											
Proportion of mature fish avoiding turbine passage		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00		
	1.00	0.84	0.87	0.89	0.92	0.93	0.95	0.96	0.98	0.99	1.00			1.00	0.85	0.87	0.89	0.91	0.93	0.94	0.95	0.97	0.98	0.99	
	0.90	0.84	0.86	0.88	0.89	0.91	0.92	0.93	0.94	0.95	0.96			0.90	0.84	0.86	0.88	0.89	0.9	0.91	0.92	0.93	0.94	0.95	
	0.80	0.83	0.85	0.86	0.87	0.89	0.89	0.9	0.91	0.92	0.92			0.80	0.84	0.85	0.86	0.87	0.88	0.89	0.89	0.9	0.91	0.91	
	0.70	0.82	0.84	0.85	0.86	0.86	0.87	0.88	0.88	0.89	0.89			0.70	0.83	0.84	0.84	0.85	0.86	0.87	0.87	0.88	0.88	0.89	
	0.60	0.82	0.83	0.83	0.84	0.84	0.85	0.85	0.86	0.86	0.86			0.60	0.82	0.83	0.83	0.83	0.84	0.84	0.85	0.85	0.85	0.86	
	0.50	0.81	0.81	0.82	0.82	0.83	0.83	0.83	0.83	0.83	0.84			0.50	0.82	0.81	0.82	0.82	0.82	0.83	0.83	0.83	0.83	0.84	
Proportion of mature fish avoiding turbine passage		0.40	0.8	0.8	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.82			0.40	0.81	0.8	0.8	0.8	0.81	0.81	0.81	0.81	0.81	0.81
	0.30	0.8	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8			0.30	0.8	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.8	
	0.20	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.79			0.20	0.79	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	
	0.10	0.78	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.78			0.10	0.79	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	
	0.10	0.78	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.78			0.10	0.79	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	
	0.10	0.78	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.78			0.10	0.79	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	
	0.10	0.78	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.78			0.10	0.79	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	

Table A6.5 Tabular values of λ for *Probarbus jullieni* and *Pangasianodon gigas* for combinations of upstream passage success and the proportion of adults passing downstream through turbines for a single dam and no exploitation ($F = 0$) under the three different assumptions of reproductive potential (High, Medium, Low).

Probarbus jullieni/High												Pangasianodon gigas/High												
		Up stream passage success rate												Up stream passage success rate										
		0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	
Proportion of mature fish avoiding turbine passage		1.00	0.88	0.9	0.91	0.93	0.94	0.95	0.96	0.97	0.99	1.00	1.00	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	
		0.90	0.87	0.88	0.89	0.9	0.91	0.92	0.92	0.93	0.93	0.94	0.90	0.91	0.91	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93	
		0.80	0.86	0.87	0.87	0.88	0.88	0.88	0.89	0.89	0.89	0.89	0.80	0.8	0.8	0.89	0.88	0.88	0.88	0.87	0.87	0.87	0.87	
		0.70	0.85	0.86	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.70	0.88	0.88	0.87	0.86	0.85	0.84	0.83	0.82	0.81	0.80	
		0.60	0.85	0.84	0.84	0.83	0.83	0.83	0.83	0.82	0.82	0.82	0.60	0.88	0.88	0.84	0.83	0.81	0.8	0.79	0.78	0.78	0.77	
		0.50	0.83	0.82	0.82	0.81	0.81	0.81	0.81	0.8	0.8	0.8	0.50	0.85	0.85	0.82	0.81	0.79	0.78	0.76	0.75	0.74	0.73	
		0.40	0.83	0.82	0.8	0.8	0.79	0.79	0.79	0.77	0.77	0.77	0.40	0.87	0.83	0.8	0.77	0.76	0.74	0.73	0.72	0.71	0.70	
Proportion of mature fish avoiding turbine passage		0.30	0.83	0.8	0.79	0.78	0.77	0.77	0.76	0.76	0.76	0.76	0.30	0.88	0.81	0.78	0.75	0.73	0.72	0.71	0.7	0.7	0.69	
		0.20	0.82	0.79	0.78	0.77	0.76	0.75	0.75	0.75	0.75	0.75	0.20	0.85	0.8	0.76	0.73	0.71	0.7	0.69	0.68	0.68	0.68	
		0.10	0.81	0.78	0.76	0.75	0.75	0.74	0.74	0.74	0.74	0.73	0.10	0.84	0.78	0.74	0.71	0.7	0.69	0.68	0.67	0.67	0.67	
	Probarbus jullieni/Medium												Pangasianodon gigas/Medium											
			Up stream passage success rate												Up stream passage success rate									
			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Proportion of mature fish avoiding turbine passage		1.00	0.87	0.88	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	1.00	1.00	0.92	0.93	0.94	0.94	0.95	0.96	0.96	0.97	0.99	1.00
		0.90	0.87	0.88	0.89	0.89	0.9	0.91	0.91	0.91	0.92	0.92	0.93	0.90	0.91	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.89
		0.80	0.86	0.86	0.87	0.87	0.87	0.87	0.87	0.88	0.88	0.88	0.88	0.80	0.9	0.89	0.88	0.87	0.86	0.85	0.85	0.84	0.83	0.83
		0.70	0.85	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.70	0.88	0.87	0.85	0.84	0.82	0.81	0.8	0.79	0.78	0.78	0.77
		0.60	0.84	0.84	0.83	0.82	0.82	0.82	0.81	0.81	0.81	0.81	0.60	0.88	0.85	0.83	0.81	0.79	0.77	0.75	0.74	0.73	0.73	0.73
		0.50	0.84	0.82	0.81	0.81	0.8	0.79	0.79	0.79	0.79	0.79	0.50	0.87	0.84	0.8	0.78	0.75	0.73	0.72	0.71	0.71	0.71	0.71
		0.40	0.83	0.8	0.8	0.78	0.78	0.77	0.77	0.77	0.77	0.77	0.40	0.86	0.8	0.76	0.73	0.72	0.71	0.69	0.68	0.68	0.68	0.68
Proportion of mature fish avoiding turbine passage		0.30	0.83	0.8	0.77	0.76	0.76	0.75	0.75	0.75	0.75	0.75	0.30	0.85	0.8	0.76	0.73	0.72	0.71	0.69	0.68	0.68	0.68	0.68
		0.20	0.82	0.79	0.77	0.76	0.75	0.74	0.74	0.74	0.74	0.73	0.20	0.84	0.79	0.74	0.7	0.68	0.67	0.66	0.66	0.65	0.65	0.65
		0.10	0.81	0.78	0.76	0.74	0.74	0.73	0.73	0.73	0.72	0.72	0.10	0.84	0.77	0.72	0.69	0.67	0.66	0.65	0.65	0.65	0.65	0.65
	Probarbus jullieni/Low												Pangasianodon gigas/Low											
			Up stream passage success rate												Up stream passage success rate									
			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Proportion of mature fish avoiding turbine passage		1.00	0.87	0.88	0.9	0.91	0.91	0.91	0.91	0.91	0.91	0.91	1.00	1.00	0.92	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
		0.90	0.86	0.87	0.88	0.89	0.89	0.9	0.9	0.91	0.91	0.91	0.90	0.9	0.9	0.9	0.89	0.89	0.89	0.88	0.88	0.88	0.87	0.87
		0.80	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.80	0.9	0.88	0.87	0.86	0.85	0.84	0.83	0.82	0.81	0.81	0.80
		0.70	0.85	0.85	0.84	0.84	0.84	0.83	0.83	0.83	0.83	0.83	0.70	0.88	0.86	0.84	0.83	0.81	0.79	0.78	0.76	0.75	0.74	0.73
		0.60	0.84	0.83	0.82	0.82	0.81	0.81	0.8	0.8	0.8	0.8	0.60	0.88	0.85	0.82	0.79	0.77	0.75	0.73	0.72	0.71	0.71	0.71
		0.50	0.83	0.82	0.81	0.8	0.79	0.78	0.78	0.78	0.77	0.77	0.50	0.87	0.83	0.79	0.76	0.73	0.71	0.7	0.69	0.68	0.68	0.68
		0.40	0.83	0.8	0.79	0.78	0.77	0.76	0.76	0.76	0.76	0.75	0.75	0.40	0.86	0.81	0.77	0.73	0.71	0.69	0.67	0.66	0.66	0.66
Proportion of mature fish avoiding turbine passage		0.30	0.83	0.78	0.77	0.75	0.75	0.75	0.74	0.74	0.74	0.73	0.30	0.85	0.8	0.75	0.73	0.69	0.67	0.65	0.65	0.65	0.65	0.65
		0.20	0.81	0.78	0.76	0.75	0.74	0.73	0.73	0.73	0.73	0.72	0.20	0.84	0.79	0.74	0.7	0.68	0.67	0.66	0.65	0.65	0.65	0.65
		0.10	0.8	0.77	0.75	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.10	0.83	0.76	0.7	0.67	0.65	0.64	0.64	0.63	0.63	0.63	0.63

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Mekong River Commission
P.O.Box 6101, Vientiane 01000,
Lao PDR. Telephone: (856) 21 263 263 Facsimile: (856) 21 263 264
E-mail: mrcs@mrcmekong.org
Website: www.mrcmekong.org