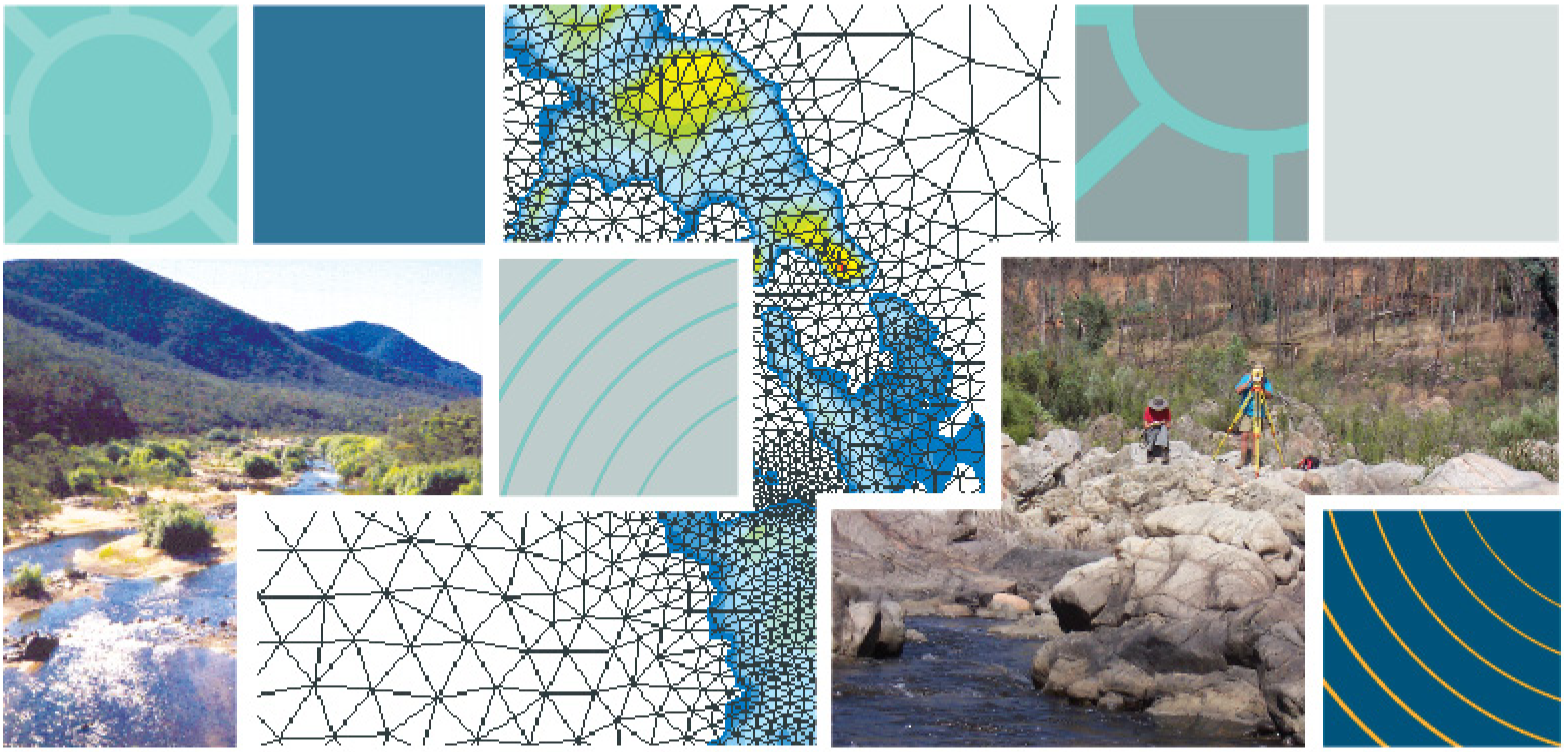
SNOWY RIVER RECOVERY

SNOWY RIVER FLOW RESPONSE MONITORING

HYDRAULIC MODELLING OF A FISH BARRIER – PINCH FALLS, SNOWY RIVER



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Abstract

A significant decline in the abundance of Australian Bass has been previously recorded in the Snowy River. This study assesses the suitability of hydraulic modelling techniques to assess a possible causative factor in the decline of Australian Bass in the Snowy River by determining the river discharge at which Australian Bass can pass upstream through discharge induced fish barriers on the Snowy River.

Pinch Falls, located 50km downstream of Snowy Falls on the Snowy River, was used as the trial reach to assess the methods proposed for the largest barrier at Snowy Falls. The Pinch Falls reach was used as it presents significant challenges for fish passage, it is has relatively easy access and has similar complexity, albeit on a smaller scale, to the main fish barrier of Snowy Falls.

A combination of one-dimensional (HEC-RAS) and two-dimensional (River2D) hydraulic models were employed at Pinch Falls with satisfactory results. It was determined using the models and the available literature that Australian bass were capable of passing through the back channels created at Pinch Falls at flows of 100 m^3s^{-1} (**8,640** Mld^{-1}) for adults, and 130 m^3s^{-1} (**11,230** Mld^{-1}) for juveniles.

An analysis of the flow record was undertaken at McKillops Bridge (located 44kms downstream and the nearest gauge with a sufficiently long record to undertake historical analysis) to determine the impacts of Jindabyne Dam upon fish passage at Pinch Falls. The results indicate that although fish passage discharge does occur at this location, they have been significantly reduced in number with the important Spring flows falling from an average of 4.6 per year to less than one per year, and the longest period between flows since the construction of Jindabyne Dam being almost 4 years.

The information gained from this study shows that the method could be transferred to other natural fish barriers along the Snowy River provided the topographical detail of the site and suitable calibration data can be obtained. The determination of the magnitude of flow required for fish passage upstream through major natural barriers is essential for the effective management of future environmental flow events from Jindabyne Dam.

Erratum: the flow value figures appearing in bold on this page are corrections made to this report in July 2010 when a typographic error was discovered. The error relates to the conversion of cumecs to ML/d.

1 Introduction

The Snowy River Flow Response Monitoring project is an interdisciplinary study of the effects of Jindabyne Dam on the hydrology, geomorphology, and ecology of the Snowy River. It is a long term project that began in its current form in 1999 (Rose and Bevitt, 2003, 2006a). The assessment of Snowy River fish community comprises an annual broad-scale survey of fish in the Snowy around a major river barrier at Snowy Falls (Gehrke *et al*., 2005), and specific fish barrier assessments (this project) of likely river discharge induced fish barriers. It is anticipated that the fish barrier assessments will assist in the interpretation of the actual long-term fish community data.

This study is a trial application of hydraulic modelling methods to predict flow depth and velocity characteristics of one known fish barrier at Pinch Falls. Should the method be successful, it may be used to assess other barriers to fish passage in the Snowy River below Jindabyne Dam, in particular Snowy Falls, a major barrier located in difficult terrain with limited access. Pinch Falls was selected for the trial on the basis of both its accessibility, and its similar channel features to those at Snowy Falls.

There are a number of factors affecting fish communities in the Snowy River, this method will assess only hydraulic factors (such as flow depth and velocity) affecting fish passage at Pinch Falls. Once the hydraulic factors are known, the frequency and duration of the flow thresholds significant to fish passage can be assessed using historical flow records to determine the impacts of Jindabyne Dam, and to aid the determination of any future environmental flow releases.

The results from a wider application of the method will provide important contextual information for the broad-scale fish survey in the Snowy River Flow Response Monitoring. There is no intention at the present time to conduct a fish passage study involving fish population surveys above and below the barriers, nor any assessment of fish barriers in tributaries. Fish passage over barriers in tributaries is not affected by reduced flows from Jindabyne Dam (although fish populations in tributaries are likely to be affected by reduced fish passage in the Snowy River).

1.1 FISH PASSAGE IN THE SNOWY RIVER

Raadik (1995) identified six key requirements for the survival and persistence of native Victorian fish species, which determine distribution patterns:

- Unimpeded passage
- Suitable habitat
- Suitable flow and water quality
- Interactions with other species
- Behavioural characteristics
- Effects of land use on habitat.

All of these factors affect fish communities in the Snowy River, but three specifically relate to river discharge. The barriers to fish passage, poor habitat quality and lack of flow as spawning triggers in the Snowy River are thought to constrain the recruitment of native fish (John Harris, *pers. comm*., 1999).

All fish must be able to move around freely within their environment, to find food, refuge and/or new habitats, move to and from breeding areas, and for juvenile dispersal (McCuckin and Bennett, 1999, Thorncroft and Harris, 2000). Fish passage is essential for the flow of genetic material within fish populations and optimal resource use, to maintain the fitness of a species and its adaptability to change (Thorncroft and Harris, 2000). Barriers to migration isolate fish populations, reducing genetic variation and fish population numbers, and can cause local extinctions above, and depleted populations downstream of barriers (Harris, 1985; Gehrke *et al*., 2001). Should fish be successful in passing a small barrier they can deplete their energy reserves and be delayed in reaching their spawning grounds, which reduces their general condition, ability to escape predators and reproductive success (Cotterell, 1988). Fish that are delayed or trapped below a barrier are also vulnerable to predation and commercial and recreational fishing. Barriers include natural features such as waterfalls, and artificial structures such as dams, weirs and road crossings.

Natural barriers probably influenced fish communities in the Snowy River prior to European disturbance. However, the construction of Jindabyne Dam, and the subsequent reduction in baseflows, floods and seasonal variability (Rose and Bevitt, 2003; Morton and Green, in press) is likely to have significantly reduced fish passage by creating low-flow induced barriers. This is expected to have impacted fish community composition and species distribution in the Snowy River. Although there have been inventories of man-made fish barriers in south-eastern Australia which include the Snowy River (Pethebridge *et al*. 1998, McGuckin and Bennett, 1999), there are no known studies available which comprehensively identify natural barriers. The major natural fish barrier known to occur on the Snowy River is the seven metre high Snowy Falls.

1.2 HYDRAULIC PREFERENCES OF AUSTRALIAN NATIVE FISH

Few studies have been undertaken to determine the hydraulic preferences of Australian native fish. The most comprehensive data set published is that of Mallen-Cooper (1992), which details the minimum depth and tolerable velocities for juvenile and sub-adult Australian bass (*Macquaria novemaculeata*) and barramundi (*Lates calcarifer*), as recorded in an experimental vertical slot fishway. Little data is readily available for the hydraulic tolerances of native fish under natural conditions, however Koehn and O’Conner (1990) do quote depth and velocity tolerances for bass movement based upon studies by Harris (1984).

This study will assess the modelled hydraulic conditions against those preferences of Australian bass as reported by Mallen-Cooper (1992) and Koehn and O’Connor (1990), these being the only data relevant to a species known to occur in the Snowy River (although recent sampling by Gilligan (in press) has failed to detect them). Mallen-Cooper (1992) reports that the maximum negotiable velocities range from 1.02ms^{-1} for 40mm juveniles up to 1.84ms^{-1} for 93mm individuals. However, these speeds can only be sustained in bursts of 2-4 seconds with a 93mm bass achieving an average burst speed of approximately 20 body lengths a second. Based on these figures, the maximum distance negotiable at the higher end of the velocity range would be approximately 3.7-7.4 metres, which compares well with figures reported by Cotterel (1998), who states that the maximum distance between resting areas in culverts should be 6 metres.

2 Study Area

Pinch Falls are located on the Snowy River in Southeast NSW, approximately 11km upstream of the Victorian border (Figure 1).

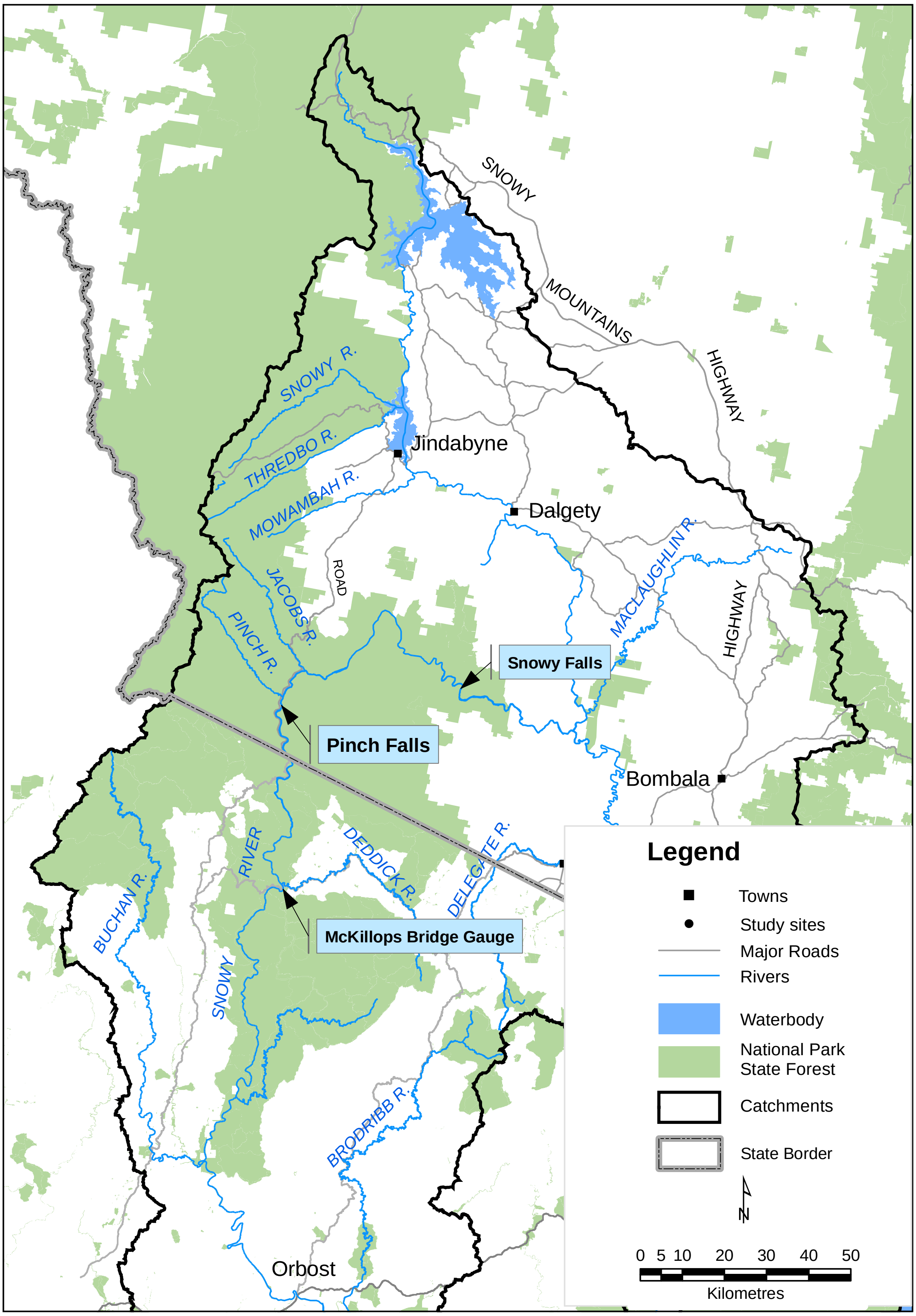

Figure 1. The Snowy River Catchment showing the location of Pinch Falls..

Pinch Falls are 2 metres high and are active under low flows. The very low flow channel is located along the left bank (Figure 2), and a dry channel on the right bank is only active under high flows (Figure 3).

Figure 2. The Snowy River at Pinch Falls during low summer flows (~3 m^3s^{-1}) showing 2 metre falls on right bank (left side of photo) and low flow channel on left bank (right side of photo). Photo: Teresa Rose, January 2004

Figure 3. The Snowy River at Pinch Falls during higher spring flows (~17 m^3s^{-1}) showing inundated channel on right bank (far left of photo) that is dry during low flows, 2 metre falls in centre, and increased flow over low flow channel on left bank (far right of photo). Photo: Robyn Bevitt, October 2001.

As discussed previously, this study is a trial application of the hydraulic modelling method. Should the method prove to be successful (and practical) the intent is to apply it to Snowy Falls, the major (natural) barrier to fish on the Snowy River. Snowy Falls are located approximately 50 kilometres upstream of Pinch Falls (Figure 1) in a remote gorge, and are 7 metres high on the right bank (Figure 4), with a complex channel composed of several smaller falls in a chasm next to the main falls, and a wide channel from the chasm across to the left bank that flows only in larger events.

Figure 4. The Snowy River at Snowy Falls during low discharge showing height of main falls. Photo: Robyn Bevitt, February 2005.

3 Methods

The hydraulic conditions at Pinch Falls were modelled using a combination of one and two-dimensional hydraulic models, utilising the HEC-RAS and River2D software suites, respectively. Modelling was undertaken using data obtained from a topographic survey of the river channel and surrounding areas. The one dimensional model was used for a preliminary analysis of the water surface profiles, and to provide estimates of upstream and downstream water surface elevations for input into the two dimensional model, River2D. Results from the two dimensional model were exported to ArcGis 9.1 Geographic Information System (GIS) software for further analysis and presentation.

3.1 TOPOGRAPHIC SURVEY

The topography of the river channel through Pinch Falls was surveyed in detail using standard survey techniques with a self-tracking robotic total station. Due to the remote location and lack of nearby benchmarks, a local datum was used and marked for future use if required. Survey detail was greatest at the low-medium flow areas of the channel and reduced with distance away from the channel on the left and right banks. Where obvious overbank or flood channels were encountered, the survey detail was again increased.

Each point surveyed was coded as a dry point, wet point or a wet edge point and the data imported into Arcview GIS. Where necessary, breakpoint lines were also noted to record important changes in slope (eg. defined bank locations or benches). The topographic points were converted into a triangulated irregular network (TIN) model using default settings in the 3D Analyst extension for Arcview. A TIN model is a three-dimensional computer representation of the surveyed landscape, and is also often also referred to as a 3D terrain model (Figure 5)

The HEC-GeoRAS extension for Arcview was used to facilitate the data transfer from the 3D terrain model to the HEC-RAS one-dimensional hydraulic model. HEC-RAS requires inputs such as cross-sections and channel and bank locations. To obtain these inputs, channel, bank and cross-sectional information is drawn at suitable locations over the terrain model using simple on-screen digitising. The topographic data for these features are extracted from the terrain model and exported to HEC-RAS automatically by the HEC-GeoRAS software, dramatically simplifying the data entry requirements of the HEC-RAS model. The use of HEC-GeoRAS also allows for greater flexibility in the building and running of HEC-RAS models as additional cross-sections can be added, or cross sections moved, at any time without the need to physically resurvey the river channel, provided there is confidence in the original topographic survey of the site.

3.2 HEC-RAS HYDRAULIC MODELLING

A combination of one and two-dimensional hydraulic models was used to predict depth and velocity over the Pinch Falls site at various flows. A one-dimensional model assumes that the water surface elevation across a cross-section remains constant and that all flow occurs perpendicular to that cross section. One-dimensional models are relatively easy to set up and calibrate. The one-dimensional model used was HEC-RAS 3.1.3, (US Corp of Army Engineers, 2007).

The HEC-RAS model was constructed and calibrated to the observed flow at the time of the topographic surveying of 3 m^3s^{-1}. The calibration flow was determined by averaging stream gauging data undertaken with a pygmy current meter and standard hydrographic methods at the beginning and the end of the surveying period. The downstream boundary condition for the calibration flow was taken as the water surface slope of the pool downstream of the surveyed area. Calibration was undertaken by adjusting the Mannings n channel roughness[1] value at each cross-section and by applying ineffective flow areas to backwater zones until the modelled water surface profiles approximated the surveyed water surface elevations. The Manning's n value which afforded the best calibration to the observed water levels for the majority of cross-sections was 0.08. This value is a little higher than some of the values published for boulder type streams such as the 0.075 calculated by Barnes (1967) but is considered adequate for the final purposes to which the one dimensional model will be used.

Following calibration, individual steady-state flows of 3-300 m^3s^{-1} were routed through the model using the mixed flow regime mode, which calculates for both sub-critical and super-critical flows (Brunner, 2002). For the lower flows, the downstream boundary condition used was the water surface slope of the most downstream pool (0.00325 $m.m^{-1}$). As flows increased and flow escaped from the main channel, the slope of the valley floor was taken to be the dominant control and the downstream boundary condition was adjusted to that of the overall valley slope (0.002 $m.m^{-1}$).

3.3 River2D TWO DIMENSIONAL MODELLING

The complexity of the Pinch Falls site was such that the limitations of the one dimensional model would prohibit its ability to accurately predict the depth and velocities of flows through some of the more complicated sections of the river channel. To obtain greater confidence in depth and velocity predictions, a two-dimensional hydrodynamic model was employed using some preliminary outputs from the HEC-RAS model. The software used for the 2D modelling was River2D, a two-dimensional depth averaged hydrodynamic and fish habitat model developed at the University of Alberta (2006) specifically for use in natural streams.[2]

River2D is a finite element mesh model (a 3D computer terrain model of the site similar to that of a TIN) and features subcritical, supercritical and wet-dry area solution capabilities (Steffler & Blackburn, 2002). The model outputs velocity components in two horizontal directions and a depth for each node. In 2D hydraulic models, velocity distributions in the vertical axis are assumed uniform. The finite element mesh is constructed using the accompanying RD2_Bed and RD2_Mesh programs. Topographic survey points and breaklines are entered into the RD2_Bed program and a bed roughness height *k* value is assigned to various areas. Steffler and Blackburn (2002) suggest that a starting point for the *k* value should be 1-3 times the largest grain diameter of bed material. Final values should be then obtained by calibrating the model to observed water surface elevations. For this study, a bed roughness height of 0.5m was used across the entire modelled area. It should be noted that estimates of bed roughness height are much less critical in 2D modelling as compared to estimates of Manning's n for one dimensional modelling (Steffler & Blackburn, 2002)

Once the bed topography is constructed, the modelled area is defined by boundaries and a uniform distribution of nodes applied over that area, initially at 10m intervals. The 3D mesh is constructed by triangulating these nodes with height data being assigned to each from the bed topography in the process. The mesh can be refined to provide more detail (smaller triangles) in the areas of greatest complexity and interest (Figure 6). The complexity of the mesh is usually a compromise between the need to adequately model complex areas versus the computing processing time available. Computing requirements increase considerably as the number of triangles in the mesh increase.

River2D requires two boundary conditions to be entered, an inflow (in m^3s^{-1}) to the upstream boundary and a water surface elevation at the downstream boundary. An estimate of the water surface elevation at the upstream boundary is also desirable for the initial condition. The more accurate this estimation, the less time taken for the model to converge and stabilise. For the observed flows, this information

[1] Manning's n is a value which represents the resistance to flow and incorporates effects of vegetation and substrate. A channel with a higher Manning's n value will generally have a higher surface water elevation than the same flow in a smoother channel of similar dimensions.

[2] It should be noted that although River2D has a fish habitat module based upon the PHABSIM weighted usable area approach, this feature of the model was not used in this study. Fish passage conditions were estimated using a more robust GIS analysis.

can be obtained from stream gauging and surveyed water levels. However in order to model flows different from that observed, it is necessary to estimate the downstream water surface elevation for each flow. These levels were estimated using the HEC-RAS model. Although it was noted previously that the one-dimensional HEC-RAS model was unable to accurately model complex channels in detail, it is more than adequate to estimate water surface elevations at the upstream and downstream boundaries of a reach, provided the flow at each of these locations is relatively uniform with little difference in elevation across the cross-section (as is the case in this study). Calibration of the 2D model was undertaken by adjusting the bed roughness values in a similar way to the HEC-RAS model. Calibration of the model was only possible at the one observed flow.

The modelled velocity and depth from the River2D model for each node were imported into Arcview GIS and converted to grids where each pixel or cell in the grid represented an area on the ground of 20cm x 20cm. Analysis of the grids was undertaken to identify each individual cell where both the depth and velocity were sufficient to allow fish movement to occur, based upon the threshold values of Mallen-Cooper (1992) discussed in section 1.2. Fish passage through the reach was deemed possible at a flow which provided these conditions in uninterrupted passage greater than a width of 60cm (ie. 3 grid cells).

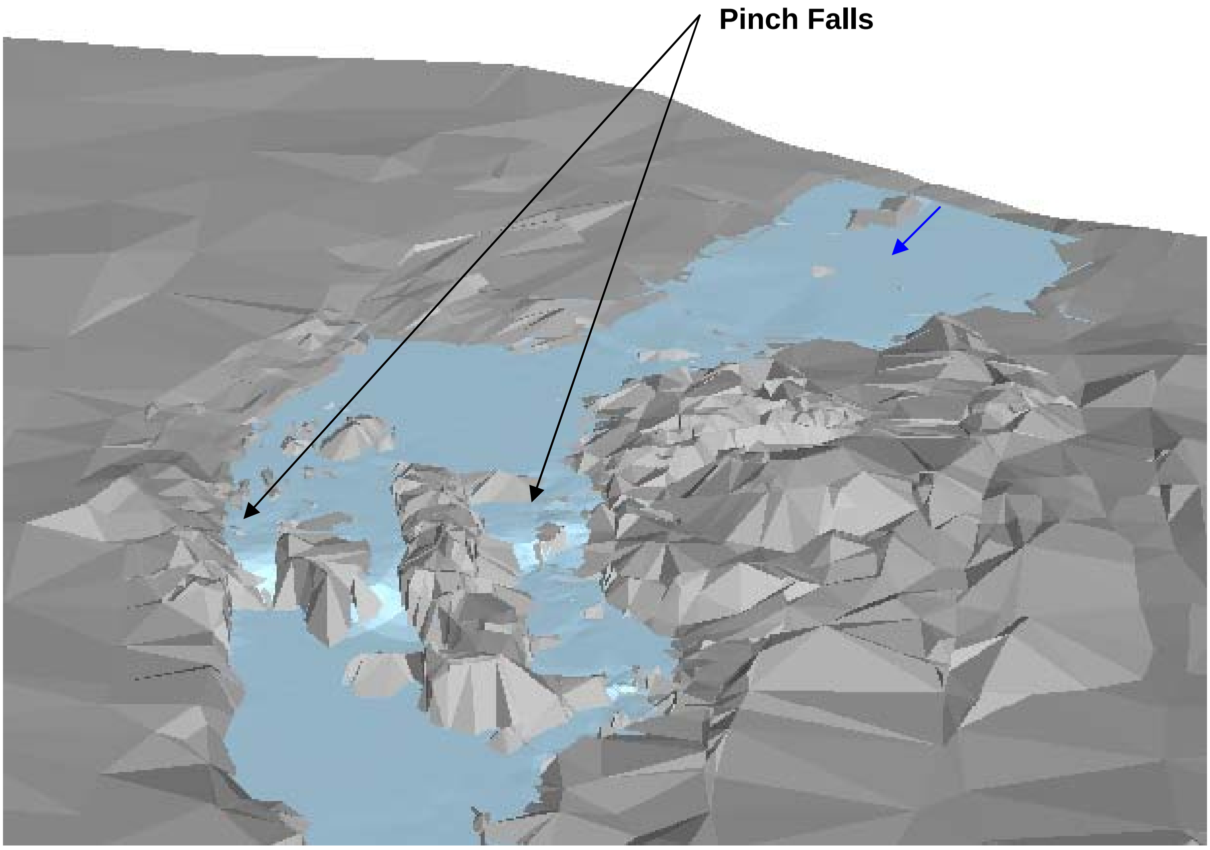

Figure 5. Triangulated Irregular Network (TIN) model of Pinch Falls (grey) showing modelled flows for 3 m^3s^{-1} in blue (looking upstream)

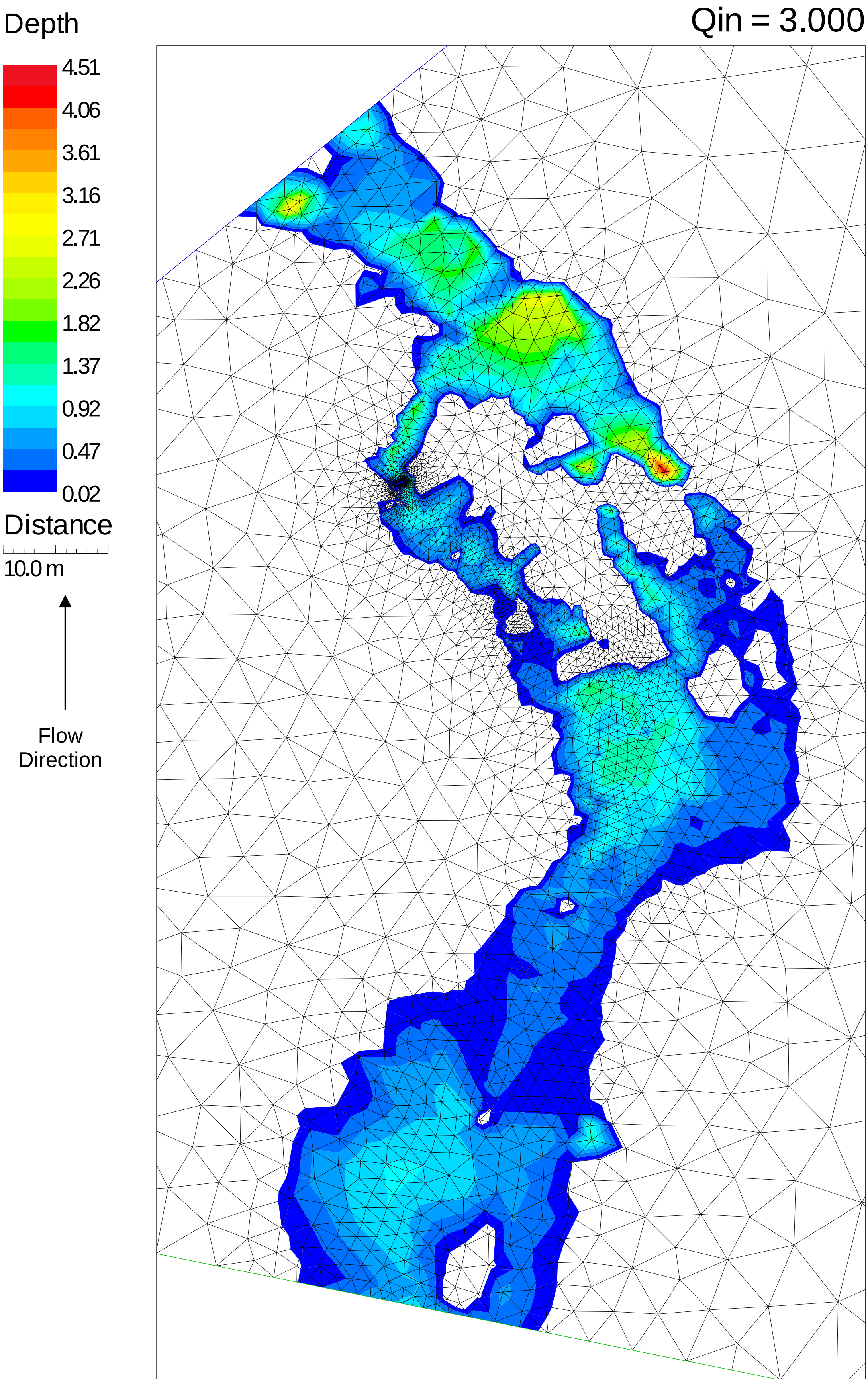

Figure 6. Example of the depth output (in metres) from the River2D model for a flow (Q) of 3 m^3s^{-1}, overlain with the finite element mesh. Note the mesh has been refined to include more detail in areas of the channel that have the greatest complexity.

3.4 HISTORICAL FLOW ANALYSIS

To assess the impacts of Jindabyne Dam on natural fish barriers such as Pinch Falls, any flow thresholds identified to be significant for fish passage by the hydraulic modelling process were assessed against the historical river discharge record.

The nearest river discharge gauge to the Pinch Falls site with sufficient flow data to enable a pre and post Jindabyne Dam analysis is located at McKillops Bridge, approximately 44 km downstream of the Pinch Falls site (Figure 1). The flow record at McKillops Bridge is a daily record extending back to March 1941. For the purposes of this study the pre-dam record is taken as the 2/03/1941 through to 22/06/1957, the date construction of the Snowy Mountains Scheme commenced. The post-dam record includes the time from the completion of Jindabyne Dam, 18/04/1967, up until the 27/02/2006. It is acknowledged that the pre-dam record of only 16 years is a little shorter than ideal for a time series analysis, but this is the only record suitable for historical analysis of flows at Pinch Falls. The only other pre-dam records that exist are above Jindabyne Dam and were considered too distant from the study site to be useful.

It should be noted that the McKillops Bridge gauge on the Snowy River has a catchment area of 10360 km^2, whilst the Pinch Fall site has a catchment area of only 8690 km^2. To account for the difference in catchment area between the gauge and the study site, a linear interpolation of flows (based on area) was used to estimate a comparable flow at the gauge for any flow occurring at Pinch Falls. Equivalent flows at the gauge were approximately 1.2 times those at Pinch Falls.

The historical flow analysis included both the generation of flow duration curves and a spell analysis. Flow duration curves for each of the flow records were produced using the IQQM software package (DLWC, 1995), and the spell analysis calculated by the RAP software package (CRCCH, 2003).

4 Results

4.1 HYDRAULIC MODELLING

HEC-RAS modelling was undertaken for river discharge of 3, 6, 9, 18, 32, 40, 60, 80 and 100 m^3s^{-1} to ascertain the flow at which fish passage was possible. During the initial analysis it became evident (through difficulties in calibration) that the HEC-RAS model was not adequately reflecting the observed flows in the mid-sections of the model where the major falls were located and where the river divides into two separate channels. The erroneous results were attributed to the one-dimensional model's inability to deal with cross sections where the water surface elevation varied significantly across the breadth of the channel (or channels). The use of HEC-RAS was therefore abandoned for the detailed assessment of fish passage and the decision made to build a two-dimensional model using River2D. The water surface elevation information from HEC-RAS for the most upstream and downstream cross-sections (Appendix 1) were however used as inputs into the River2D model boundary conditions. The HEC-RAS outputs were considered acceptable for this task as the single channel in these locations was much less complex and calibration with the observed flow was possible in the immediate vicinity.

River 2D modelling was undertaken for flows of 3, 18, and 40 m^3s^{-1}, and then in 10 m^3s^{-1} increments up to 120m^3s^{-1}. The results of the 2D modelling provide a useful insight into the likelihood of fish passage through the Pinch Falls reach as detailed information is provided for both velocity and depth. As mentioned previously, the level of detail can be adjusted according to need by adjusting the size of the mesh used in the calculations. For most flows, the size of the triangles used in the mesh varied from 8 m to 0.1 m between nodes, and in the subsequent analysis this has been transformed to provide information in grids with a 0.2 m pixel size.

Fish navigable areas are defined where depth is greater than 20cm and velocity is less than 1.84 ms^{-1} (Mallen-Cooper, 1992). Figure 7 shows the navigable area for the flows of 3, 18, 40 and 100 m^3s^{-1} (approximately 260, 1,600, 3,500, and 8,700 MLd^{-1}, respectively). At the observed flow of 3 m^3s^{-1}, fish passage is not contiguous throughout the reach due to insufficient depth over cascades in the low flow channel. At 18 m^3s^{-1}, flow begins to pass over the main falls but depth remains the limiting factor in the low flow channel. At 40 m^3s^{-1}, depth is no longer a limiting condition in the low flow channel, however velocities across the cascades are far too high for fish to pass, and depth and velocity over the falls are both limiting factors. It is not until flows reach 100 m^3s^{-1} that fish passage is possible through the reach. At this flow, two secondary or by-pass channels have formed, one on either bank. A major flood channel on the right bank is also evident however the model does not extend sufficiently downstream to determine whether this is navigable by fish. In any case, the channel on the left bank does provide passage at this flow, albeit at the higher end of the velocity range quoted by Mallen-Cooper (1992).

Figure 8 provides a more detailed view of the 100 m^3s^{-1} flow suitable for a finer degree of analysis. It is evident that in order for fish to pass through the by-pass channel on the left bank they will be required to navigate two zones of velocities up to 1.84 ms^{-1}. This is in the higher range of navigable velocities for bass greater than 93 mm but potentially too fast for smaller fish. The most downstream of these higher-velocity navigable areas is approximately 6 metres in length which is within the quoted distance range that fish can sustain their maximum burst speeds (3.7-7.4 m). Fish will then be required to transverse another 3-4 metres of velocities up to 1 ms^{-1} before reaching a resting zone (assumed to be velocities less than 0.3 ms^{-1}). This scenario is repeated some 15 m further upstream with the exception that the high velocity flow section is perhaps one or two metres shorter. It should therefore be theoretically possible for bass of greater than 90 mm in length to pass through the Pinch Falls reach at a flow of 100 m^3s^{-1}, but it is not clear whether smaller fish would be able to pass.

Figure 7. Fish navigable areas at 3, 18, 40 and 100 m^3s^{-1} based upon depth being greater than 20cm and velocity less than 1.84 ms^{-1} (Mallen-Cooper, 1992). Note that fish passage does not occur until a by-pass channel is formed on the left bank at 100 m^3s^{-1}.

It is noted that Mallen-Cooper (1999) reports that the size of Australian bass generally increases with distance from the tidal limit. Individuals found in the vicinity of the tidal limit are reported to be around 40mm in length, with size increasing to 60-90mm for those individuals found in the middle reaches, and those found in the upper reaches being generally greater than 120mm. Given this information, it would be expected that most individuals of bass found in the Pinch Falls reach would be in the 60-90mm range. Despite this, it was considered important to determine the flows at which smaller bass might be able to pass Pinch Falls, particularly as the natural size distribution of Australian bass within the Snowy River may be impacted upon by the release of fingerling-sized individuals in any potential fish re-stocking programs.

Bass fingerlings of 40mm probably do not require 20cm of depth, in fact Richardson (1984) is cited in Koehn and O'Conner (1990) as reporting that juvenile bass may only require a depth of 3 cm (however the authors do not define the dimensions of a juvenile). In any case, further analysis of the 100 m^3s^{-1} model was undertaken to ascertain whether there would be a suitable low-velocity path through the reach at the 10 or 3 cm depth thresholds. At the 10cm depth, a continuous path does exist at velocities less than 1.02 ms^{-1}, however it occurs in one section at only 1 pixel width (20 cm). At a 3 cm depth this path is only slightly wider (Figure 9) and just on the assumed limit of 60 cm.

Further modelling was carried out to ascertain at which flow (if any) one could confidently predict that smaller fish could pass through the reach. To allow for some margin of error, the original depth and velocity conditions provided by Mallen-Cooper (1992) were adopted (ie. > 20 cm and < 1.02 ms^{-1}, respectively) together with a >60 cm width. It is not until a flow of 130 m^3s^{-1} occurs that these conditions are met (Figure 9).

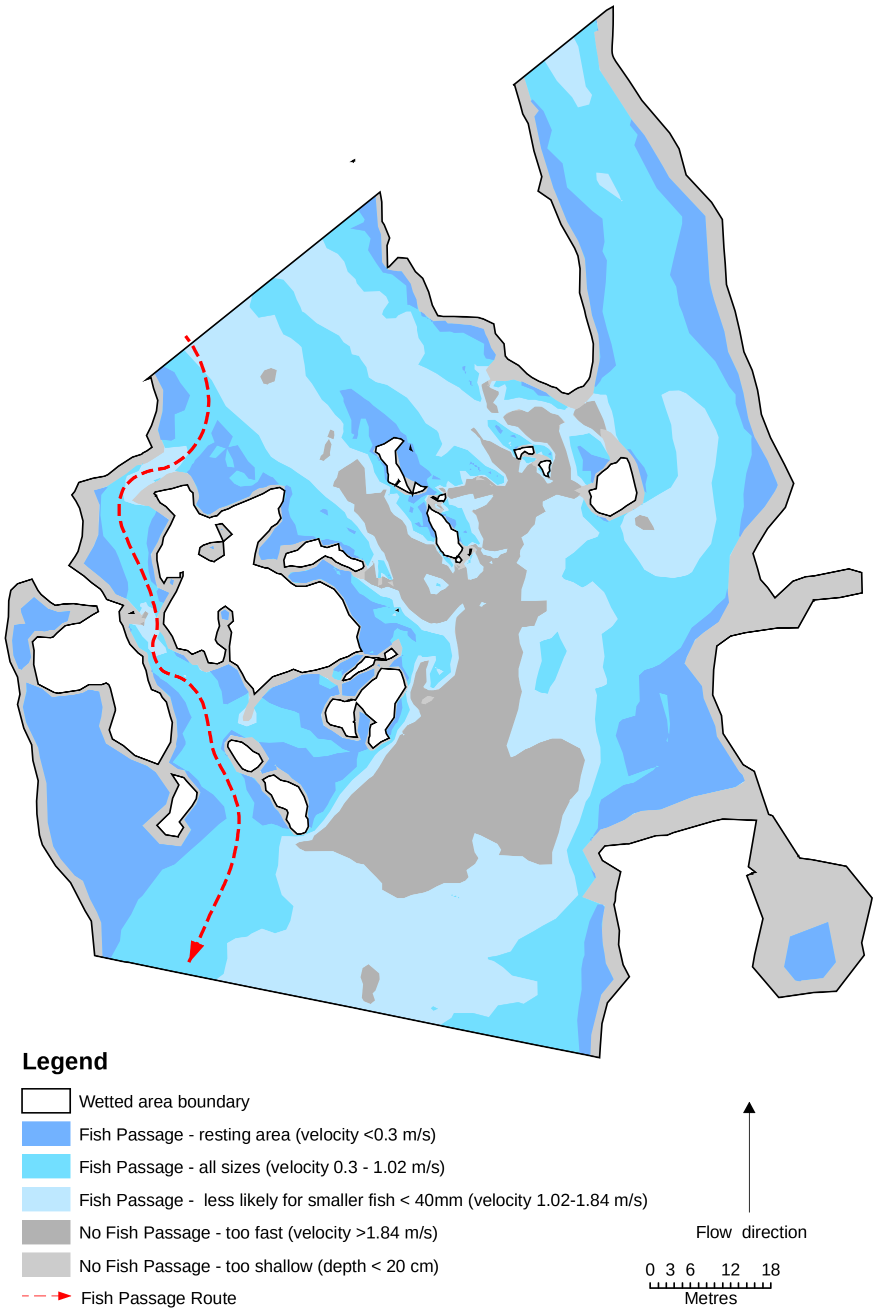

Figure 8. Modelled fish passage conditions for adult fish at a flow of 100 m^3s^{-1}.

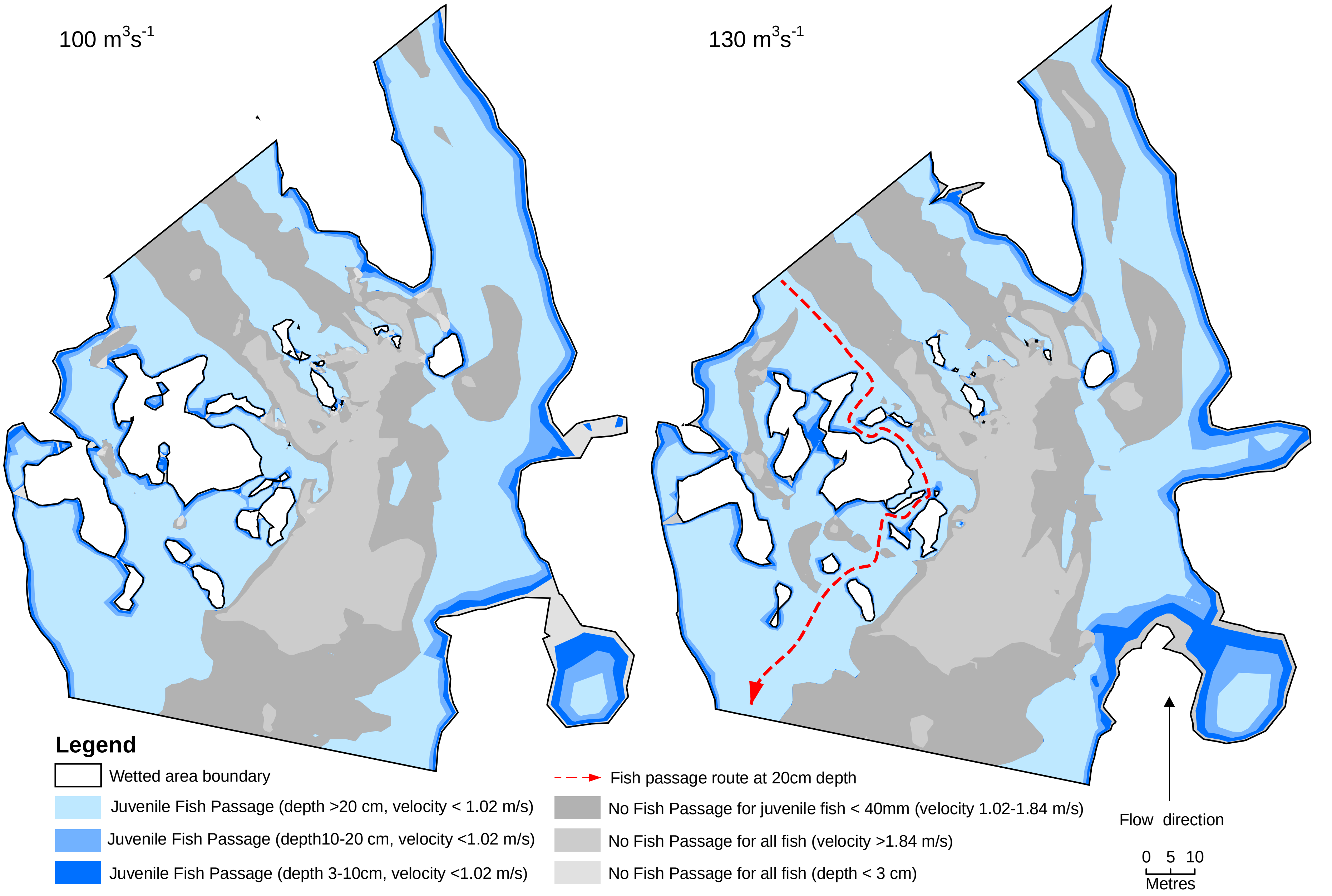

Figure 9. Modelled fish passage conditions for juvenile fish at flows of 100 m^3s^{-1} and 130 m^3s^{-1}

4.2 HISTORICAL FLOW ANALYSIS

The modelling results indicate that adult Australian bass require a flow of 100 m^3s^{-1} through the Pinch Falls reach before passage upstream is possible, with juvenile bass requiring up to 130 m^3s^{-1}. As mentioned previously, in order to obtain equivalent flows at the gauge site, flow values at Pinch Falls require an adjustment to account for the differences in catchment area between the two sites. Using this multiplication factor of approximately 1.2, a flow of 100 m^3s^{-1} at Pinch Falls is equivalent to a flow of 120 m^3s^{-1} at McKillops Bridge, and a flow of 130 m^3s^{-1}, equivalent to 156 m^3s^{-1}. The analysis of the historical flow records uses the values at McKillops Bridge as the threshold values, and these are referred to as “fish flows”. It should be noted that this assessment assumes that conditions remain suitable for fish passage once the threshold flows have been passed.

4.2.1 Flow Duration Analysis

Figure 10 shows the pre and post-dam flow duration curves for the McKillops Bridge gauge. It is evident that a flow of 120 m^3s^{-1} (10,370 Mld^{-1}) or greater would have occurred approximately 13 percent of the time before Jindabyne Dam was built and a flow of 156 m^3s^{-1} (13,350 Mld^{-1}), approximately 8% of the time. Following construction of the scheme, these flows only occur approximately 2% of the time.

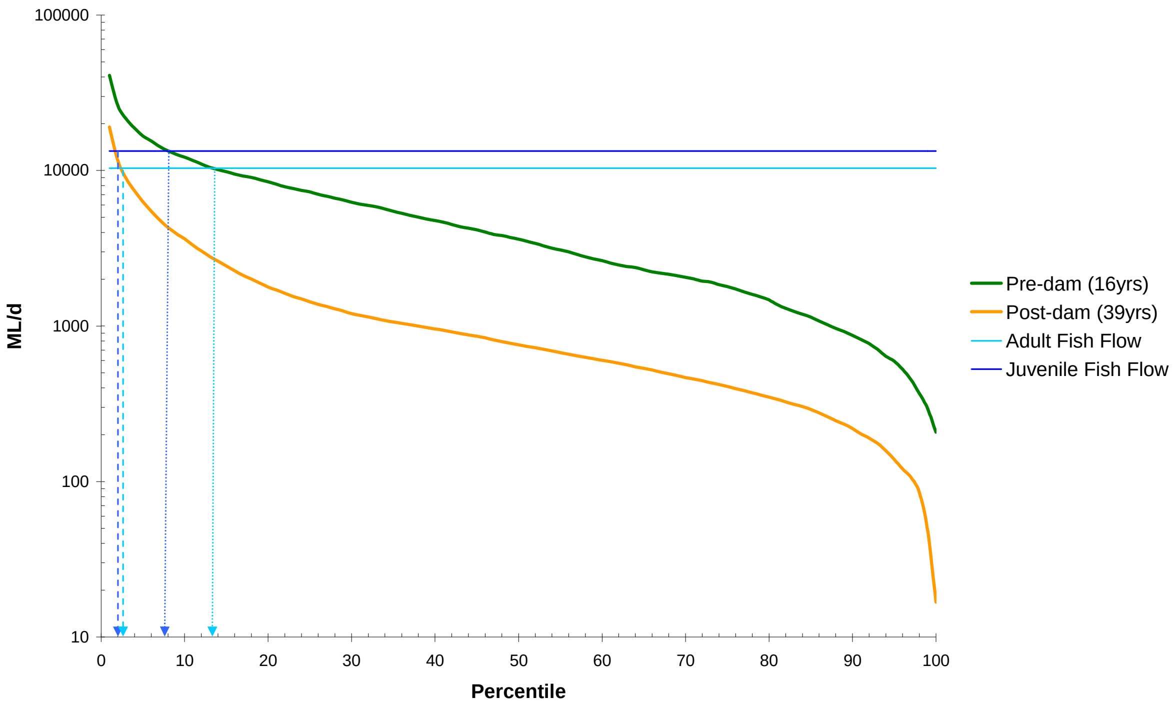

Figure 10. Flow duration curves for pre and post dam conditions at McKillops Bridge gauge for the adult and juvenile fish flows of 120 and 156 m^3s^{-1} (equivalent to 10,370 and 13,350 Mld^{-1}, respectively).

4.2.2 Fish Flow Spell Analysis

A spell analysis of the fish flows of 120 m^3s^{-1} and 156 m^3s^{-1} was undertaken on both the pre and post-dam flow records with record lengths of 16 and 39 years, respectively. For this analysis, a “spell” is defined as a flow event with a flow greater or equal to the fish flow. Individual spells must be separated by a period greater than one day where flows are below the fish flow threshold. Table 1 summarises the results of this spell analysis.

Table 1. Spell analysis for pre and post-dam construction for adult and juvenile Australian bass.

	Pre-dam Conditions		Post-dam Conditions	
	Adult	Juvenile	Adult	Juvenile
Start of analysis	2/03/1941		18/04/1967	
End of analysis	22/06/1957		27/02/2006	
Length of record (years)	16.31		38.86	
Minimum flow (m^3s^{-1})	2.41		0.19	
Maximum flow (m^3s^{-1})	3,090		4,676	
Fish Flow Spells				
Fish flow threshold (m^3s^{-1})	120	156	120	156
Fish flow threshold (Mld^{-1})	10,370	13,350	10,370	13,350
Number of fish flow spells	144	112	87	66
Mean duration of fish flow spells (days)	5.11	3.96	3.84	3.33
Mean period between fish flows spells (days)	34	46	157	209
Longest period between fish flows (days)	314	315	1411	1464
Mean number of fish flow spells per year	8.83	6.87	2.24	1.70
Spring				
Mean number of fish flow spells	4.56	3.19	0.90	0.58
Mean duration of fish flow spell (days)	4.66	4.46	2.86	2.67
Summer				
Mean number of fish flow spells	0.63	0.44	0.24	0.24
Mean duration of fish flow spell (days)	5.00	3.96	5.95	3.60
Autumn				
Mean number of fish flow spells	1.44	1.38	0.42	0.32
Mean duration of fish flow spell (days)	4.25	3.37	2.59	2.44
Winter				
Mean number of fish flow spells	2.50	2.06	0.82	0.63
Mean duration of fish flow spell (days)	5.47	3.41	3.79	3.27

As would be expected the construction of the Snowy Mountains Scheme, and in particular the commissioning of Jindabyne Dam has resulted in a significant reduction in the number of events that would allow fish migration upstream through the Pinch Falls reach. Before the dam was constructed, fish flows for adult bass occurred, on average, 8.3 times per year. Following construction this has been reduced to just 2.2 times. For juvenile fish, the average number of events reduces to 6.9 and 1.7 per year, respectively. The average period between fish flows for the pre-dam conditions was 46/34 days (adult/juvenile) with the current situation now between 157/209 days. The longest period on the record between fish flows for the pre-dam conditions was 315/314 days, with this increasing to 3.9/4.0 years for the post-dam conditions.

A seasonal assessment of the occurrence of fish flow spells is provided in Figure 11. For the pre-dam conditions, fish flows most commonly occurred in Spring and Winter with averages of 4.5 and 2.5 flow events per season, respectively. Following the dam construction, the seasonal variability of the flow events is significantly reduced to less than one, with Spring and Winter now experiencing only slightly more fish flow events than summer and autumn (Table 1, Figure 11).

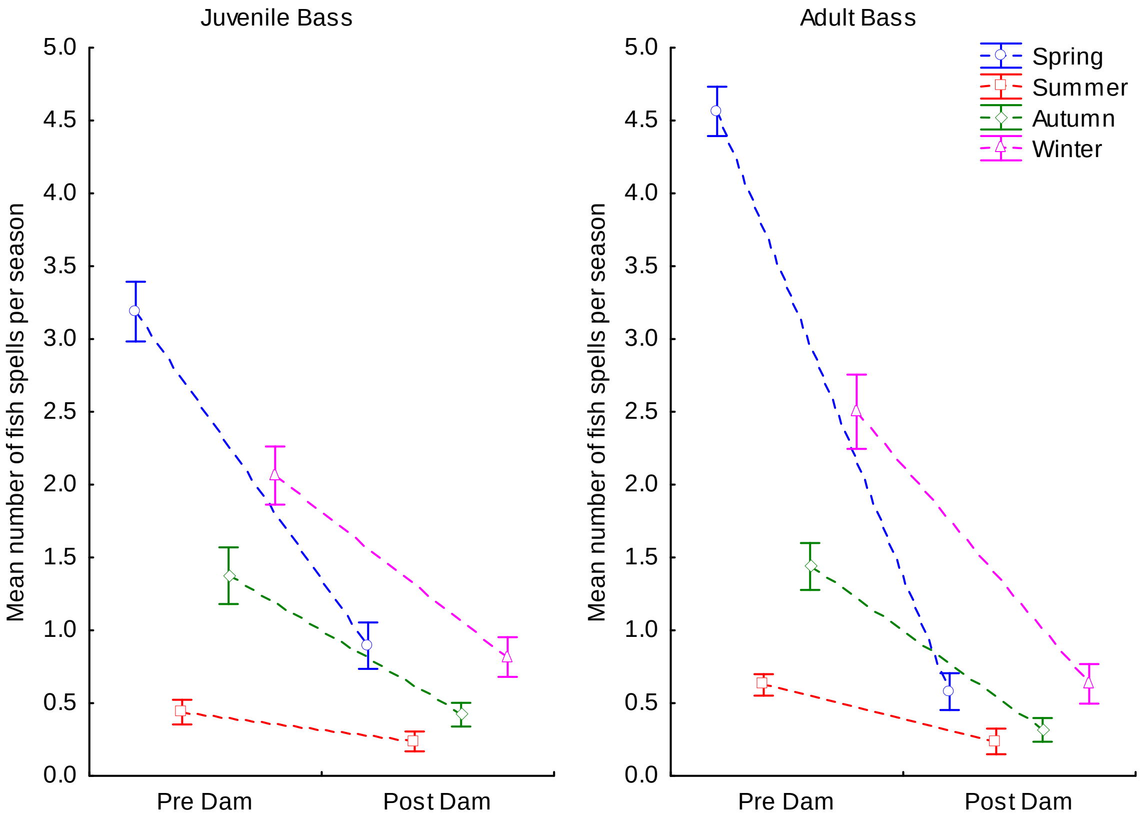

Figure 11. Mean number of fish flow spells per season at the Snowy River at Pinch Falls for pre and post Jindabyne Dam conditions for adult and juvenile Australian bass.

5 Discussion

The primary objective of this study was to trial the use of hydraulic modelling methods to determine the flows at which fish passage was possible through a natural barrier. Pinch Falls was selected for its accessibility and similar complexity to the main fish barrier of Snowy Falls, with the expectation that should the method be successful, it would be applied to the more remote Snowy Falls reach (Figure 1). The following discussion deals with the difficulties encountered during the course of this study, and how these might effect the application of the method in a more rugged and remote environment such as the Snowy River at Snowy Falls.

5.1 SURVEYING

Surveying within the channel was often difficult and dangerous. The survey was undertaken at a time of relatively low flow. Deep water in pools and high velocities through cascading chutes resulted in some areas being too dangerous to survey, particularly as the consequences of slipping and being taken downstream were dire. In these cases, shots above the water line were obtained by shooting directly to the rock surface (rather than using a survey prism), a feature available in the automatic total station used in this study. Difficult shots within the channel were obtained from the banks where possible using this method but in some cases “dummy” shots were estimated and included in the surveyed data. Should the flow have been greater during the survey period, significantly more areas would have been inaccessible and the survey less precise. This is likely to be a significant restriction in Snowy Falls which are much higher and have dangerous secondary falls in a deep chasm.

The initial survey of the low flow areas was probably too detailed for the purposes of the study. The flows required to drown out the falls, and to create the by-pass channels required for fish passage, were much larger than initially envisaged. The modelling of such flows requires less detail in low-medium flow areas, so less time should be spent on this in future surveys and more time spent extending the coverage area, both laterally and longitudinally, to ensure all possible by-pass channels are included in the modelled area.

5.2 HYDRAULIC MODELLING

It was initially planned to model the area with just the one-dimension HEC-RAS software. It quickly became evident that the limitations of the 1D model were too great for the complexity of the Pinch Falls reach with it’s multiple water surface levels across a cross-section. The modelling of flows through natural fish barriers requires the use of a two-dimensional model such as River2D in conjunction with a 1D model. Two-dimensional models can provide the more detailed analysis of depth and velocity required for fish passage estimation by modelling flows both longitudinally and laterally through the use of a three dimensional mesh rather than cross-sectional data.

All models need adequate calibration to provide some level of certainty in the results. The HEC-RAS model used in this study was only able to be calibrated at the relatively low flows that occurred at the time of surveying. The River2D model could also only be calibrated at these low flows for wetted area and depth. No calibration was possible for velocity. The absence of this calibration at high flows does cast some uncertainty on the results, however this is unavoidable given the lack of high flows to calibrate against and the inherent danger and difficulties in obtaining measurements of depth and velocity should they occur.

5.3 SUITABILITY OF THE METHOD FOR SNOWY FALLS

This study has shown that the combination of one and two-dimensional hydraulic modelling techniques can be useful in estimating the flows required for fish passage through Pinch Falls. The largest data input required is a three dimensional topographic or terrain model of the area. For this study the topographic model was obtained through standard survey techniques. Pinch Falls is a smaller and more accessible site than Snowy Falls. The size and complexity of the Snowy Falls site, coupled with its remote and inaccessible location, would make the surveying of the site expensive and potentially dangerous.

It was previously noted that the level of detail required in the survey is much less than initially thought. The modelling of the larger flows needed for fish passage requires less detail over a greater spatial extent than smaller flows. Once flows are sufficient to escape from the low to moderate flow channels into the overbank areas, the level of detail required in the low flow areas decreases substantially. Given the remoteness of the Snowy Falls site, it may be possible to obtain the topographic model at an appropriate level of detail required for modelling, through remote sensing means (either ortho-rectified aerial photography or laser based techniques). The difficulties would be: 1) determining topography below vegetation and below the water surface where remote sensing techniques generally cannot penetrate, and 2) the ability of the air borne laser altimeters to measure the complex topography of the channel, with large vertical variations in the bed occurring within very short horizontal distances. Regardless of whether this information can be obtained, the very large flows being modelled creates greater uncertainty in the model, and inaccuracies in the topography measured at the low flow levels are unlikely to be as significant an impact upon the overall uncertainty of the model.

6 Conclusion

The aim of this study was to assess the suitability of hydraulic modelling techniques to determine the flows at which fish can pass through natural fish barriers on the Snowy River. Pinch Falls was used as a trial reach due to its significant challenges for fish, it's easy accessibility and its similarity on a smaller scale to the main fish barrier Snowy Falls.

A combination of one-dimensional (HEC-RAS) and two-dimensional (River2D) hydraulic models were employed with satisfactory results. It was determined that Australian bass were capable of passing through the back channels created at Pinch Falls at flows of 100 m^3s^{-1} for adults, and 130 m^3s^{-1} for juveniles (equivalent to **8,640** and **11,230** Mld^{-1}, respectively).

An analysis of the flow record was undertaken at McKillops Bridge (located 44kms downstream and the nearest gauge with a sufficiently long record to undertake historical analysis) to determine the impacts of Jindabyne Dam upon fish passage at Pinch Falls. The results indicate that fish flows do continue to occur at this location, but they have been significantly reduced in number with the important Spring flows falling from an average of 4.6 per year to less than one per year, and the longest period between flows since the construction of Jindabyne Dam being almost 4 years.

The information gained from this study shows that the method could be transferred to other natural fish barriers along the Snowy River provided the topographical detail of the site and some observed calibration data can be obtained. The determination of the magnitude of flow required for passage through major barriers is essential for interpreting the data from the broad scale fish survey for the Snowy River and the effective management of future environmental flow events from Jindabyne Dam.

Erratum: the flow value figures appearing in bold on this page are corrections made to this report in July 2010 when a typographic error was discovered. The error relates to the conversion of cumecs to ML/d.

7 References

Bevitt, R. (2000) Snowy River Benchmarking Project: Fish Component: Recruitment Study. Confidential draft document, NSW Department of Land and Water Conservation, Cooma. August 2000. 9 pp.

Barnes, H. H. (1967) Roughness characteristics of natural channels. US Geological survey water-supply paper 1849. United States Government Printing Office, Washington 1967.

Brunner, G.W. (1992) HEC-RAS, River Analysis System Hydraulic Reference Manual. US Army Corps of Engineers Hydrological Engineering Centre, Davis CA, USA. 350pp.

Cotterell, E. (1998) Fish passage in streams: Guidelines for design of stream crossings. Queensland Department of Primary Industries, Brisbane, August 1998. 37 pp.

CRCCH (2003) River Analysis Package software. CRC for Catchment Hydrology (now eWater CRC), Canberra. (www.toolkit.net.au/rap accessed 2.7.2007)

DLWC (1995) Integrated Quantity-Quality Model (IQQM), Reference Manual. *DLWC Report No. TS94.048, Parramatta, NSW, Australia.*

Freshwater Ecology (2000) Lower Snowy River Native Fish Recruitment Study 2000/01: Equipment and Tasks. Prepared for NSW Department of Land and Water Conservation and East Gippsland Catchment Management Authority. Freshwater Ecology, Arthur Rylah Institute for Environmental Research, 123 Brown Street, Heidelberg, Victoria. August 2000. 7 pp.

Gehrke, P.C., Gilligan, D.M. and Barwick, M. (2001) Fish communities and migration in the Shoalhaven River – Before construction of a fishway. NSW Fisheries Final Report Series No.26. Sydney Catchment Authority, Cooperative Research Centre for Freshwater Ecology and NSW Fisheries, Port Stephens.

Gehrke, P.C., Bevitt, R., Miners, B., Jones, H., Harris, J., Rose, T., and Kathuria, A. (2005) Chapter 8. Broadscale Fish. In:. *Specific sampling designs.* Snowy River Flow Response Monitoring Project: Snowy River Recovery, Report No. 3. Rose, T. A., and Bevitt, R. (eds.) (2005*)* Department of Natural Resources. Cooma, NSW.

Gilligan, D. (in press*). Assessment of fish assemblages in the Snowy River, NSW, 1999-2004: Pre- and Post- First Environmental Flow Release.*: Snowy River Flow Response Monitoring Project, Snowy River Recovery. Department of Infrastructure Planning and Natural Resources. Cooma, NSW.

Harris, J. H. (1984) A survey of fishways in streams of coastal south-eastern Australia. *Aust. Zool.* 21:219-233.

Harris, J. H. (1985) Concern over dams' effects on fish populations in south-east Australia. *Australian Fisheries.* 44(4): 37-42.

Koehn, J.D. and O'Connor, W.G. (1990) Biological information for management of native Freshwater Fish in Victoria. Department of Conservation and Environment Freshwater Fish management Branch, Arthur Rylah Institute for Environmental Research, Melbourne.

Mallen-Cooper, M. (1992). Swimming ability of juvenile Australian bass, *Macquaria novemaculeata* (Steindachner), and juvenile barramundi, *Lates calcarifer* (Bloch), in an experimental vertical-slot fishway. *Australian Journal of Marine & Freshwater Research*, **43**, 823-834.

Mallen-Cooper, M (1999) Taking the mystery out of migration. In: *Fish Movement and Migration.* Australian Society for Fish Biology Workshop Proceedings Bendigo,Victoria 28-29 September 1999. Donald A. Hancock, David C. Smith and John D. Koehn (eds.). Australian Society for Fish Biology, Sydney.

McCuckin, J. and Bennett, P. (1999) State fishway program: An inventory of fishways and potential barriers to fish movement and migration in Victoria. Waterways Unit Department of Natural Resources and Environment, Victoria.

Morton, S. and Green, D. (in press). Hydrological changes in the Snowy River downstream of Jindabyne Dam after the first flow release from the Mowamba River. Snowy River Flow Response Monitoring Project: Snowy River Recovery. NSW Department of Water and Energy.

Pethebridge, R., Lugg, A. and Harris, J. (1998) Obstructions to fish passage in New South Wales South Coast Streams. Cooperative Research Centre for Freshwater Ecology, Canberra, and NSW Fisheries, Sydney. May 1998. 69 pp.

Raadik, T.A. (1995) Native fishes of Victoria – their significance, distribution and general biology. 14 pp. In: Willows, Weeds and Native Fish, Summer Conference, Geelong, 20 November 1995. River Basin Management Society, Victoria.

Raadik, T.A., Close, P.G. and Conallin, A.J. (2001) Lower Snowy River Fish Recruitment Study 2000/2001: Pilot Project Report. Report to the Department of Land and Water Conservation. Arthur Rylah Institute for Environmental Research, 123 Brown St, Heidelberg, Victoria. May, 2001. 38 pp.

Richardson, B. (1984) *Instream flow requirements in relation to the biology and ecology of freshwater fishes in the Tweed River N.S.W.*, M.Sc. Thesis, Macquarie university, NSW 129pp.

Rose, T.A. and Bevitt, R. (2003) Environmental Flows Initiative Technical Report to Environment Australia: Summary Progress Report on available data from 1999-2001. Snowy River Recovery: Snowy River Flow Response Monitoring Project, Report No. 5. NSW Department of Natural Resources. Cooma, NSW.

Rose, T.A. and Bevitt, R. (2006) Project background and development. Snowy River Snowy River Flow Response Monitoring Project: Snowy River Recovery, Report No. 1. NSW Department of Natural Resources. Cooma, NSW.

Steffler, P. and Blackburn, J. (2002). *River2D Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat*. University of Alberta, Canada, September 2002.

Thorncroft, G. and Harris, J.H. (2000) Fish passage and fishways in New South Wales: A status report. Cooperative Research Centre for Freshwater Ecology Technical Report 1/2000. NSW Fisheries and Cooperative Research Centre for Freshwater Ecology, Sydney. 32 pp.

University of Alberta (2006). River 2D. http://www.river2d.ualberta.ca/. Accessed 2.7.2007

US Corp of Army Engineers (2007). HEC RAS. http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html. Accessed 29.6.2007

8 Appendices

Appendix 1. HEC-RAS Output Table

Profile	Q Total	Min Ch El (m3/s)	W.S. Elev (m)	Crit W.S. (m)	Vel Chnl (m)	Flow Area (m/s)	Top Width (m2)	Froude # Chl (m)
Pinch Falls Upstream Cross-section River Station No. 135.327								
PF 1	3	98.65	99.61	98.95	0.18	16.47	27.68	0.08
PF 2	6	98.65	99.76	99.06	0.29	20.76	31.1	0.11
PF 3	9	98.65	99.87	99.14	0.38	24.36	35.92	0.13
PF 4	18	98.65	100.11	99.33	0.57	34.11	45.5	0.17
PF 5	32	98.65	100.4	99.52	0.74	50.36	66.84	0.2
PF 6	35	98.65	100.46	99.55	0.77	54.1	67.73	0.2
PF 7	40	98.65	100.54	99.61	0.8	59.74	69.97	0.21
PF 8	45	98.65	100.61	99.66	0.84	65	72.15	0.21
PF 9	50	98.65	100.68	99.71	0.87	70	73.27	0.22
PF 10	60	98.65	100.81	99.8	0.93	79.14	74.97	0.22
PF 11	70	98.65	100.92	99.92	0.99	88.26	88.3	0.23
PF 12	80	98.65	101.02	100.01	1.03	97.48	94.16	0.23
PF 18	90	98.65	101.11	100.06	1.08	106.09	99.32	0.24
PF 13	100	98.65	101.18	100.17	1.13	113.26	103.91	0.25
PF 14	110	98.65	101.25	100.26	1.17	121.6	110.41	0.25
PF 19	110	98.65	101.25	100.26	1.17	121.6	110.41	0.25
PF 15	120	98.65	101.32	100.31	1.21	129.12	115.77	0.25
PF 16	130	98.65	101.38	100.37	1.26	135.56	120.17	0.26
PF 17	150	98.65	101.48	100.5	1.34	148.58	130.2	0.27
PF 20	300	98.65	102.19	101.08	1.66	260.65	171.44	0.3
Pinch Falls Downstream Cross-section River Station No. 16.762								
PF 1	3	95.95	96.65	96.24	0.4	7.57	14.33	0.17
PF 2	6	95.95	96.94	96.36	0.51	11.83	15.37	0.18
PF 3	9	95.95	97.17	96.45	0.58	15.44	16.21	0.19
PF 4	18	95.95	97.69	96.67	0.74	24.42	18.12	0.2
PF 5	32	95.95	98.24	96.93	0.92	35.88	23.8	0.21
PF 6	35	95.95	98.34	96.97	0.95	38.27	24.57	0.21
PF 7	40	95.95	98.49	97.06	1	42.14	25.78	0.22
PF 8	45	95.95	98.63	97.13	1.05	45.92	26.93	0.22
PF 9	50	95.95	98.77	97.2	1.09	49.63	28.03	0.22
PF 10	60	95.95	99.02	97.34	1.16	56.81	30.03	0.23
PF 11	70	95.95	99.24	97.46	1.22	63.85	32.27	0.23
PF 12	80	95.95	99.45	97.58	1.28	70.78	34.45	0.23
PF 18	90	95.95	99.64	97.69	1.33	77.73	39.86	0.23
PF 13	100	95.95	99.81	97.79	1.38	85.02	45.57	0.24
PF 14	110	95.95	99.97	97.91	1.42	92.64	50.67	0.24
PF 19	110	95.95	99.97	97.91	1.42	92.64	50.67	0.24
PF 15	120	95.95	100.11	98.02	1.46	100.2	53.83	0.24
PF 16	130	95.95	100.25	98.13	1.49	108.14	60.53	0.24
PF 17	150	95.95	100.51	98.32	1.56	126.23	79.69	0.24
PF 20	300	95.95	101.62	99.41	1.82	276.42	173.57	0.25