Habitat improvement and creation for threatened dwarf galaxias (*Galaxiella pusilla*) along the Dandenong Creek corridor

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Key Points
• Critical elements of dwarf galaxias habitat design include shallow, still-slow flowing water and dense submerged and emergent vegetation. Natural partial wetting and drying regimes are also likely to be important for increasing food resources and decreasing predator abundance. • Intermittent connectivity between habitats during floods is essential for dwarf galaxias dispersal along waterway corridors and persistence of metapopulations. • The risk of invasion by predators or competitors such as eastern gambusia during floods can be balanced by providing habitats with varying degrees of hydrologic connectivity, as well as habitat drying when invasions occur. • Fish stocking should maximize genetic diversity, adaptability and resilience of populations.

Abstract
The dwarf galaxias (*Galaxiella pusilla*) is a threatened freshwater native fish from south eastern Australia. Along Dandenong Creek and its floodplain, as in many parts of its range, dwarf galaxias habitats have been degraded and fragmented as agricultural and urban areas have expanded. Their habitats (e.g. wetlands, swamps, billabongs and small streams) have been impacted by the creation of drainage channels, direct filling, piping, channel incision, concrete-lining, levees, vegetation clearing and changes in hydrology. The spread of invasive fish, especially eastern gambusia (*Gambusia holbrooki*), has placed further pressure on dwarf galaxias populations from predation and competition. In 2013, Melbourne Water initiated a large-scale conservation project that aims to re-establish a sustainable dwarf galaxias metapopulation along an approximately 18 kilometre reach of Dandenong Creek in the south eastern suburbs of Melbourne. This project involves the creation or improvement of 20 inter-connected floodplain habitats, as well as fish breeding and translocation. Here we describe the habitat designs, particularly the importance of natural wetting and drying regimes, and the need for intermittent connectivity between habitats during floods for dispersal and colonisation. We balance the risk of invasion by exotic fish during floods with the need for dwarf galaxias dispersal by providing habitats with varying degrees of hydrologic connectivity. We also outline our approach for establishing a genetically diverse breeding stock and subsequent translocations, as well ongoing monitoring to assess the success of the project.

Keywords
Galaxiella pusilla, freshwater fish, habitat design, translocation.

Introduction
As the global population continues to increase and pressures from human activities intensify, biodiversity has been steadily declining worldwide with freshwater ecosystems particularly vulnerable (e.g. Dudgeon et al. 2006). For example, in Australia a total of 36 freshwater fish species are currently listed as threatened within the *Australian National Environment Protection and Biodiversity Conservation (EPBC) Act 1999*, another 25

listed within Australian State or Territory legislation, and 13 species nationally listed by the Australian Society for Fish Biology (Lintermans 2013). One of these species, the dwarf galaxias (*Galaxiella pusilla*), is listed as 'vulnerable' on the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (IUCN 2013), the *EPBC Act 1999*, the *Tasmanian State Government Threatened Species Protection Act 1995*, and the *Victorian State Government Flora and Fauna Guarantee (FFG) Act 1988*. A recent taxonomic revision by Coleman et al. (2015) identified that the dwarf galaxias, as it was formally known, consisted of two species (now *G. pusilla* or dwarf galaxias in eastern Victoria and Tasmania, *G. toourtkoourt* or little galaxias in western Victoria and South Australia) based on substantial genetic and morphological differences e.g. total length, number of vertebrae, position of dorsal to anal fins, ventral markings. Due to a large range reduction (essentially halving the distribution), consistently lower genetic diversity within populations (Coleman et al. 2010; Coleman et al. 2013), and extent of human disturbance to their habitats (especially greater Melbourne), the dwarf galaxias likely qualifies as 'endangered' consistent with the status proposed by the State of Victoria (DSE 2013). Commonly cited threats to dwarf galaxias are habitat loss and fragmentation, changes in hydrology (including climate change), water pollution and interactions with invasive species – particularly eastern gambusia (or mosquitofish), *Gambusia holbrooki*, that can impact dwarf galaxias by predation, fin nipping, and competition for food resources and habitat (e.g. Koster 2003; Saddlier et al. 2010).

In 2013, Melbourne Water initiated a large-scale conservation project that aims to re-establish a dwarf galaxias metapopulation over an approximately 18 kilometre reach of Dandenong Creek in the south eastern suburbs of Melbourne (Fig. 1). Along Dandenong Creek and its floodplain, as in many parts of its range, dwarf galaxias habitats have been degraded and fragmented as agricultural and urban areas have expanded. Their habitats (e.g. wetlands, swamps, billabongs and small streams) have been impacted by the creation of drainage channels, direct filling, piping, channel incision, concrete-lining, levees, vegetation clearing and changes in hydrology, to the point where only two sites along the creek are known to support dwarf galaxias populations. This project involves the creation or improvement of 20 inter-connected floodplain habitats, as well as fish breeding, translocation and monitoring. Here we focus on our approach to habitat designs, with an overview of the fish stocking strategy and ongoing monitoring.

Dwarf galaxias

Dwarf galaxias are small (up to ~40mm total length) freshwater fish typically found in habitats that are shallow, still-slow flowing, with semi-permanent water and dense submerged and emergent aquatic vegetation. This includes swamps, wetlands, billabongs, shallow lakes, small streams and earthen drains (e.g. Saddlier et al. 2010; Coleman et al. 2015). They feed mostly on microcrustacea (e.g. copepods, cladocerans, ostracods) as well as small aquatic (e.g. chironomids, ceratopogonids) and terrestrial insects (Humphries 1986). Dwarf galaxias are an annual species that die soon after spawning (semelparity), although adults occasionally survive across breeding seasons (Romanowski 2004; Coleman et al. 2017). Spawning appears to be triggered by heavy rain between late autumn-early spring, at which time they can use flood waters to access suitable habitats (Humphries 1986; Romanowski 2004; Coleman et al. 2017). Eggs are laid singly on stems and under the leaves of aquatic plants, such as *Persecaria*, *Crassula* and *Myriophyllum* (Backhouse and Vanner 1978; Humphries 1986; Coleman et al. 2014). Little is known of the water quality tolerances of dwarf galaxias, although measurements across the entire distribution include ranges of 5.8 to 24.8 ^{o}C for water temperature, 18.2 to 130 % for dissolved oxygen, 5.0 to 7.8 for pH, 36 to 3,070 µS/cm for electrical conductivity and 1.0 to 133 NTU for turbidity (Coleman et al. 2015).

Many of the floodplain habitats and small streams where dwarf galaxias occur have substantial seasonal and inter-annual fluctuations in water levels – contracting to small pools in dry periods and expanding across floodplains or transitioning into flowing streams in wet periods (Coleman et al. 2017). Dwarf galaxias have adapted to these dynamic environments by an ability to air-breathe and survive weeks (to potentially months) without surface water in the presence of moisture e.g. under detritus, aquatic vegetation or crayfish burrows (Coleman et al. 2017). While floods provide opportunities for dwarf galaxias dispersal along waterway corridors, there is an associated risk of invasion by predators or competitors such as eastern gambusia. Coleman et al. (2017) demonstrated that the ability of dwarf galaxias to air-breathe can be used to their advantage by artificial drying of habitats where eastern gambusia invade. Wetting and drying cycles are also likely to be important for dwarf galaxias from the perspective of food resources and predators. Prolonged inundation can result in successional shifts of invertebrate communities from those dominated by food resources (e.g. Ostracoda, Copepoda, Cladocera) to those dominated by predators (e.g. Odonata, Dytiscidae, Nepidae and Notonectidae) which is likely to be detrimental to dwarf galaxias densities (Romanowski 2004; Coleman et al. 2017). Wetting and drying cycles can also be important for wetland productivity, including increased species richness and biomass of aquatic plants (e.g. Junk et al. 1989; Cassanova and Brock 2000). Large inter-annual fluctuations in dwarf galaxias population densities observed in the wild, where there is a continual process of local extinction and recolonisation amongst habitats in the landscape, indicate that dwarf galaxias exist in metapopulations i.e. a population of populations (e.g. Hanski 1998). Accordingly, successful conservation of dwarf galaxias likely requires protecting and restoring interconnected habitats, as well as recognising the importance of habitats that may be unoccupied from time to time (Coleman et al. 2017).

Habitat Design Principles

Based on the habitat characteristics and life cycle requirements of dwarf galaxias described above, the key design principles for habitats along Dandenong Creek were to; 1) *provide a range of habitat opportunities* along the creek corridor that are inter-connected during floods, consistent with establishment of a sustainable metapopulation where the risk of population loss is spread across the landscape, 2) *maximise the use of existing habitat features* such as remnant wetlands and billabongs, that already had some desirable elements (e.g. mature aquatic and riparian vegetation) and required less costly modifications and shorter habitat maturity periods, 3) *ensure a dense cover of submerged and emergent aquatic vegetation* throughout the habitat, by adopting a generally shallow and gradual bed profile, and planting of a diversity of species, 4) c*reate conditions that mimic substantial natural wetting and drying of habitats*, in part by the shallow/gradual bed profile described in '3' and also through the provision of refuge pools, local water diversions and adjusted height of outlets, 5) provide *protection from eastern gambusia* by incorporating a suite of habitats with varying frequency of connection during floods. This balances the need for dwarf galaxias dispersal with the risk of invasion by eastern gambusia by having sites that are frequently connected during floods (e.g. every 3-6 months) but have a high risk of eastern gambusia invasion, with those that are rarely connected during floods (e.g. >10 years) but have a low risk of eastern gambusia invasion i.e. 'insurance sites' and 6) *minimise maintenance* by avoiding the use of features requiring intensive manual operation (e.g. pumps and weir adjustments). In the event that eastern gambusia invade the habitats, the majority of sites have a small area (i.e. about 3000 m^2 habitat area; 300m^2 refuge pool area) and can be relatively easily reset by pumping them dry, while the larger sites have outlet structures to assist drying where necessary.

Habitat Designs

Following initial habitat assessments (area, water depth, substratum composition, vegetation cover and composition, water quality) and fish surveys (dip nets and bait traps) between Dandenong and Bayswater in November-December 2013, a total of 26 sites were selected for works scoping and habitat design. Modifications to each site to improve the habitat for dwarf galaxias included combinations of: 1) creating refuge pools (where sites completely dry from time to time), 2) diversion of local drainage such as local catchment diversions, direct connection with adjacent creeks or wetlands (to increase water security), 3) installation of an outlet to allow draining in the event of eastern gambusia invasion, 4) significant reprofiling of existing habitat or complete construction of habitat on the floodplain and 5) planting of aquatic and terrestrial vegetation. Given the relatively small-scale and low complexity of works, the objective of the habitat designs was to just define the critical elements and general requirements for each site (i.e. 'functional designs'). Functional designs were based on standard drawings for the refuge pools and water source connections, while the layout was informed by a water balance analysis, existing habitat condition (e.g. vegetation cover and composition, bed form) and site inspections with stakeholders to identify opportunities and constraints. Although at some sites key features required survey heights, set-out markers were placed to guide construction prior to works commencing at all sites.

At the landscape-scale, the aim was to provide connectivity between sites in floods to facilitate dwarf galaxias dispersal and restore the metapopulation structure within the system. Five clusters of sites were identified along the creek corridor, namely (Fig. 1): 1) Winton wetlands, 2) Koomba Park, 3) Shephards Bush/Jells Park, 4) Mulgrave Reserve and 5) Police Paddocks. To balance the need for connectivity of dwarf galaxias between habitat sites with the threat of eastern gambusia invasion, a suite of sites with varying hydrologic connectivity during floods within each habitat cluster were chosen, including 'insurance' sites that are unlikely to be invaded by eastern Gambusia and could be used as a source of stock for future translocations if necessary. The flood levels along Dandenong Creek were determined to assess the degree of connectivity between habitat sites. Based on flow data at two gauges along Dandenong Creek (Police Road, Rowville and Wantirna Road, Heathmont) and LiDAR derived channel cross-sections, it was estimated that the creek overtops approximately 3-4 times per year. 100-year and 10-year flood levels were taken from Melbourne Water's HEC-RAs model for most of the 18 km reach, showing that all sites except for one are within the 100 year ARI flood extents.

At the site-scale, priorities were to provide shallow, still-slow moving water, dense aquatic vegetation, and a gradual grading of the bed to support vegetation diversity and accentuate wetting and drying regimes. A typical habitat included a refuge pool to ensure that there will always be some water available in warmer/drier times, whilst preserving a much larger habitat area that is able to wet and dry throughout the year (Fig. 2a). Refuge pools are up to 1m below the base of the habitat area they sit within, comprise around 10-15% of the total habitat surface area, have a gentle slope (approximately 1 (V): 10 (H)) and were lined with a minimum 0.75 mm (30 mil) polyethylene liner to reduce water losses from infiltration. At least 20cm of soil was placed on the top of the liner to allow for establishment of aquatic plants.

Water balance modelling of selected sites was undertaken using MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (eWater 2016) to understand the reliability of the water supply and to ensure that habitats do not completely dry out. Inflow to each site was assumed to be runoff from the local catchment (which in most cases was dominated by parks and reserves where there was a low risk of poor water quality), with no significant contributions from groundwater. To determine the minimum water depth for refuge pools (including a notional buffer depth of 0.3m), modelled 'dry periods' were assumed to have no inflow or outflow to an infinitely deep refuge pool subject to evaporation and infiltration. The catchment sizes for each habitat were determined from a digital elevation model, and catchment nodes split into the following land use types and fraction impervious values: Residential (0.45), Parks and reserves (0.1-0.2), Industrial zones or roads (0.8). The habitat sites were modelled as ponds with the area and volume set as per the desktop and site analysis. Rainfall data was taken from a gauge adjacent to Dandenong Creek at Rowville and two subsets of the dataset used: (i) 2013-2014 to verify the model with on-site observations during site inspections in November-December 2013 and late January 2014, and (ii) a set of six dry years were taken from the full historic record (36 years) for habitat resilience testing (1986, 1990, 2004, 2005, 2009 and 2013). Potential evapotranspiration rates were derived from measurements at Koo Wee Rup (closest location) with an average daily value of 2.82 mm and a maximum of 4.84 mm. Seepage from habitat sites was estimated at 0.36 mm/hr (average 8.64 mm/day) for heavy to medium clay sand (e.g. eWater 2016). Accordingly, a maximum drawdown of 13.48 mm/day was adopted. Daily fluxes of inflow, outflow, water storage and water levels were extracted from MUSIC (6-minute time steps for historic data, daily time step for 2013-2014) and the evaporation and seepage that would have occurred on that day was subtracted from the pool volume for each day over the duration of the dry period to understand maximum drawdown, and consequently the minimum design depth of the refuge pool (Fig. 2b).

Invasion by eastern gambusia can be managed by drying out habitats (e.g. Ayres and Clunie 2010; Coleman et al. 2017). Drying can be done relatively easily by manually pumping smaller refuge pools, however, for larger refuge pools outlet structures were installed. Outlets comprised a gate valve that can be locked shut and manually opened to drain pools to around 100 mm maximum water depth (Fig. 3a). Outlet pipes were deliberately large (~450 mm diameter) to reduce maintenance due to blockage from sediment. Where a refuge pool alone was insufficient to provide a permanent wetted area, options for the diversion of local water sources (e.g. adjacent drains or wetlands) were investigated. Similar to the outlet design, these diversions incorporated a gate valve that can be manually opened and closed to manipulate water supply. The standard design included two pipes constructed in parallel to provide a backup option should the filter media become clogged with sediment, and a filter media (sand and/or gravel) installed in part of the connection to prevent invasion from eastern gambusia with the water supply (Fig. 3b).

Planting densities and composition aimed to be reflective of natural aquatic vegetation communities along the Dandenong Creek corridor. Given that most of the works were associated with the construction of refuge pools, planting largely focused on aquatic species with some terrestrial planting where works were more extensive. Planting plans were structured around 6 planting zones: 1) terrestrial, 2) wetland margin (+300mm to Normal Water Level (NWL)), 3) ephemeral/shallow marsh (NWL to -150mm), 4) shallow marsh/deep marsh (-150mm to -400mm), 5) deep marsh/submerged marsh (-400mm to -750mm), and 6) fully submerged marsh (< -750mm). Typical species lists and planting densities are provided in Table 1.

Fish stocking strategy

A fish stocking strategy for dwarf galaxias was developed in 2014 with the aim to maximize genetic diversity, adaptability and resilience of dwarf galaxias populations along the creek corridor. Available genetic data (microsatellites) from natural dwarf galaxias populations (Coleman et al. 2010; 2013) were used to develop the optimal composition of the founder population and numbers for future translocations to habitats based on simulations with a purpose-built program in R (DwarfGenSim). In June 2015, based on those simulations, 40 adult (1:1 sex ratio) dwarf galaxias were collected from 12 locations across the Dandenong and Westernport catchment in greater Melbourne. These fish were introduced into Melbourne Water's Hallam Valley Conservation Wetland (Narre Warren) that was built in 2006 for breeding dwarf galaxias. Translocations from the founder population into sites along the Dandenong Creek corridor, with at least 500 adults (1:1 sex ratio) per site, will take place in March-April each year when adults are close to breeding. The translocation strategy is progressive where, as fish are moved between sites, those sites also become potential source sites in the following year. Provided populations within some of the sites, within each cluster, remain large (greater than 1000 individuals), a genetically diverse metapopulation structure is expected. The first translocation of dwarf galaxias from the founder population occurred in March 2017, where 600 individuals were moved to Tirhatuan Wetlands, Rowville.

Monitoring

The Key Performance Indicator (KPI) for this project is that there will be 'sustainable populations of dwarf galaxias by 30th June 2018'. This is to be measured by fish surveys demonstrating the presence of juveniles in at least one habitat in each habitat cluster. Once habitats have been constructed and translocations of fish have occurred, the proposed monitoring program will involve three components; (i) annual fish surveys (using bait traps set for 24 hours) to evaluate dwarf galaxias population size and the presence of invasive species at a site, (ii) annual genetic analyses (collection of at least 30 fin clips from each population) to determine genetic variability and effective population size within and between sites, and (iii) surveys of environmental conditions (e.g. continuous water level loggers, and during fish surveys, assessments of vegetation cover and diversity, water quality, invertebrate abundances and composition). Restoration of floodplain habitats is also expected to benefit other aquatic species such as frogs, aquatic invertebrates and waterbirds. Accordingly, novel approaches have been incorporated into the monitoring strategy using environmental DNA (eDNA) techniques, to not only provide complementary estimates of fish abundances, but also to detect other biodiversity that benefits from the habitat sites (e.g. frogs, birds, turtles) before and after works. In addition, on-going monitoring will include maintenance inspections during site establishment (first 2-3 years) and required responses (e.g. infill revegetation, weed control, modifications to refuge pool depth), or operation of gate valves at connections to drain sites after floods if eastern gambusia are present.

Conclusions

This project is a landscape-scale restoration effort for threatened dwarf galaxias in the Dandenong Creek corridor. At the time of writing this paper, 17 of the 20 habitats had been constructed and planted, with the remaining three habitats schedule for completion by mid-2018. Habitat construction at each site involved only small-scale earthworks, and due to the sensitive nature of the sites, small-medium size machinery was used (e.g. backhoe, truck with tipper body). Further translocations of fish into these sites are expected to occur progressively over the next 2-3 years. On-going monitoring of habitats will determine the factors that lead to particularly successful dwarf galaxias populations, providing critical information to further refine dwarf galaxias habitat design.

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Table 1. Plant species lists and indicative percentage composition by wetland zone

Terrestrial (0.5-4 plants/m^2)	Wetland Margin +300mm to NWL (6 plants/m^2)	Ephemeral/Shallow Marsh NWL to -150mm (6 plants/m^2)		Shallow Marsh/ Deep Marsh -150 to -400mm (4 plants/m^2)
Eucalyptus yarraenesis	*Acaena novea-zealandiea 5*	*Baumea arthrophylla 10*	*Lobelia pratioides 2*	*Alisma plantago-aquatica 5*
(5-8 per site)	*Austrodanthonia laevis 2*	*Bolboschoenus medianus 10*	*Myriophyllum crispatum 5*	*Baumea articulate 15*
Goodenia ovata 5	*Carex appressa 15*	*Carex appressa 8*	*Neopaxia australasica 2*	*Bolboschoenus medianus 10*
Leptospermum lanigerum 15	*Carex gaudichaudiana 10*	*Carex fascicularis 8*	*Persicaria decipiens 5*	*Eleocharis sphacelata 20*
Melaleuca ericifolia 25	*Juncus amabilis 8*	*Centella cordifolia 5*	*Ranunculus inundatus 2*	*Myriophyllum crispatum 10*
Rubus parvifolius 5	*Juncus gregiflorus 8*	*Craspedia paludicola 5*	*Triglochin alcockiae 5*	*Schoenoplectus tabernaemontani 20*
Gahnia sieberiana 10	*Lepidosperma laterale var majus 5*	*Crassula helmsii 5*	*Villarsia reniformis 5*	*Triglochin procerum 20*
Lomandra longifolia 20	*Lepidosperma longitudinale 5*	*Eleocharis acuta 10*		**Deep Marsh/Submerged Marsh -400 to -750mm (1-4 plants/m^2)**
Poa labillardierei 20	*Lomandra longifolia 10*	*Isolepis inundata 2*		
	Lycopus australis 2	*Juncus pallidus 3*		
	Persicaria decipiens 5	*Juncus procerus 4*		*Myriophyllum verrucosum 10*
	Poa labillardierei 20	*Juncus sarophorus 3*		*Potamogeton cheesmanii 20*
	Xerochrysum palustrus 5	*Lilaeopsis polyantha 2*		*Triglochin procerum 30*
				Vallisneria americana 40
				Fully Submerged Marsh <-750mm (1 plants/m^2)
				Vallisneria americana 100

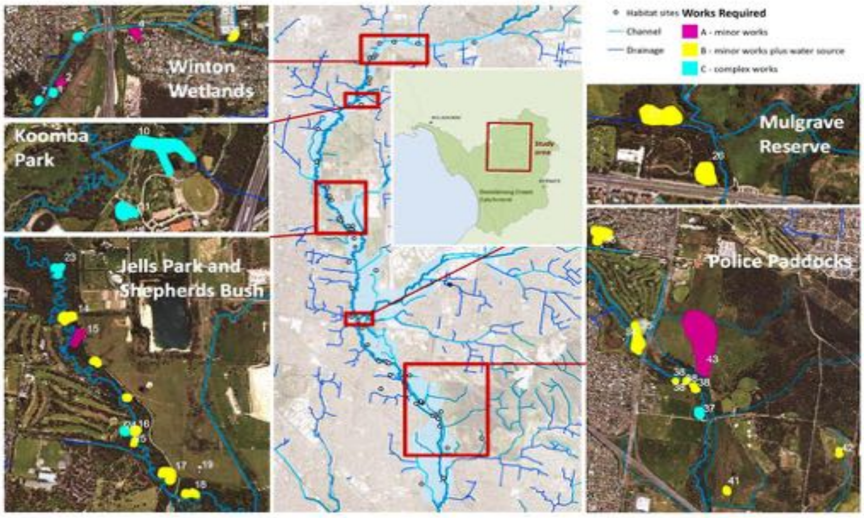
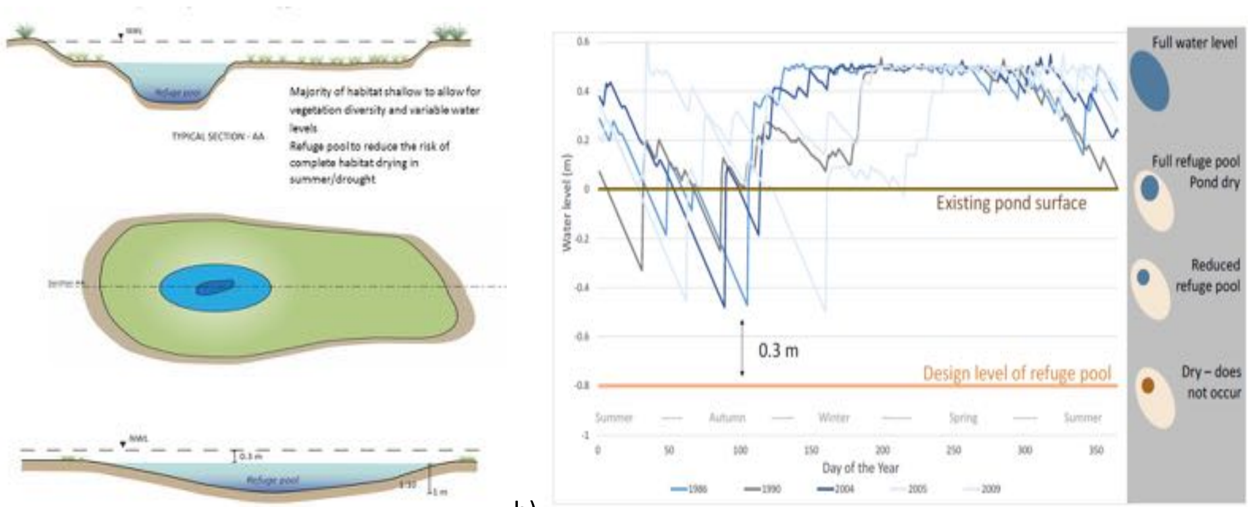
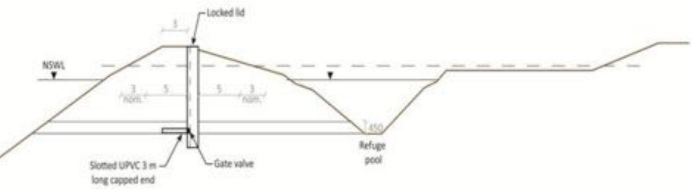


Figure 1. Dandenong Creek habitat sites from Bayswater to Dandenong, including the five nominal habitat clusters. No works proposed for sites 3,7,18,19,24 and 34.

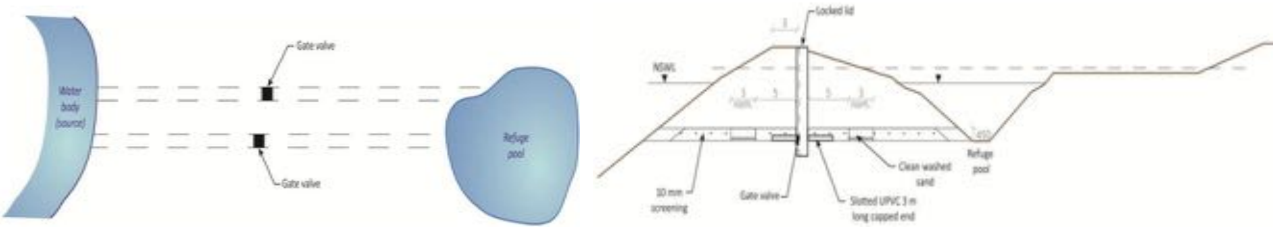


a) b)

Figure 2. a) typical dwarf galaxias habitat design and b) example MUSIC modelling results for determination of the minimum refuge pool depth



a)



b)

Figure 3. Standard design for a) habitat outlets and b) diversions from local water sources