PREDICTING THE OUTCOMES OF HYDROLOGICAL CHANGE IN AQUATIC HABITATS OF NORTHERN AUSTRALIA

This document introduces and overviews the main components of the flow habitat modelling approach provides a demonstration of its application using a series of case study examples

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CSIRO

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Project overview

Background and introduction:

Riverine, wetland and floodplain biota require suitable habitat conditions including inundation extent, depth and velocity for their persistence.

Natural variability, climate change and possible future water resource development is expected to result in different flow conditions within riverine, floodplain and wetland habitats.

Hydrodynamic modelling supports exploration of change in flow conditions associated with possible scenarios of change while providing a richer set of environmental variables compared to 'flow at the gauge'.

Ecological change can be explored and predicted based upon understanding the habitat associations and flow preferences of biota, enabling us to dynamically model flow habitat as an ecological response across space and time.

Project goal:

'To develop a spatio-temporal habitat suitability model for water dependent biota of northern Australia using metrics of flood dynamics produced by hydrodynamic models.'

Terms and acronyms

Acronyms	
AEP	Annual Exceedance Probability
ER	Ecosystem Respiration
GCM	Global Climate Model
GLM	Generalized linear model
GPP	Gross Primary Productivity
HD modelling	Hydrodynamic modelling
NAWRA	Northern Australia Water Resource Assessment (Project)
RF	Random Forest model
SDM	Species distribution model
WRD	Water resource development

Term	What the term means
Baseline scenario	Baseline scenarios demonstrated in this document are for three flood events (representing AEP 1:2, 1:10 & 1:25) for the Finniss catchment in the Northern Territory
Climate scenarios	Wet and dry climate scenarios representing the 10th of 90th percentiles of possible future long-term rainfall changes
Commence-to-fill	The flow threshold at which the river overbanks and water spills over onto the floodplain
Development scenarios	Dam development scenario representing changes in stream flow due to creation of medium to large instream infrastructure
Flow	Movement of water down the watercourse (longitudinally), or onto the floodplain (laterally). Important aspect of flow include the timing, depth, velocity, duration and frequency of the flow event
Functional group	A group of species that share characteristics of response
Habitat	An area where resources, both physical and biotic, are available that support both breeding (e.g. availability of nesting sites) and/or survival (e.g. providing food and shelter)
Scenario	*Scenario* is used to describe the overarching conditions being explored/evaluated. This can include natural variability, development scenarios and climate change Scenarios are often compared to a baseline (scenario) to evaluate outcomes relative to the baseline or counter factual
Workflow	The software tools and/or processing steps required to implement the scientific method

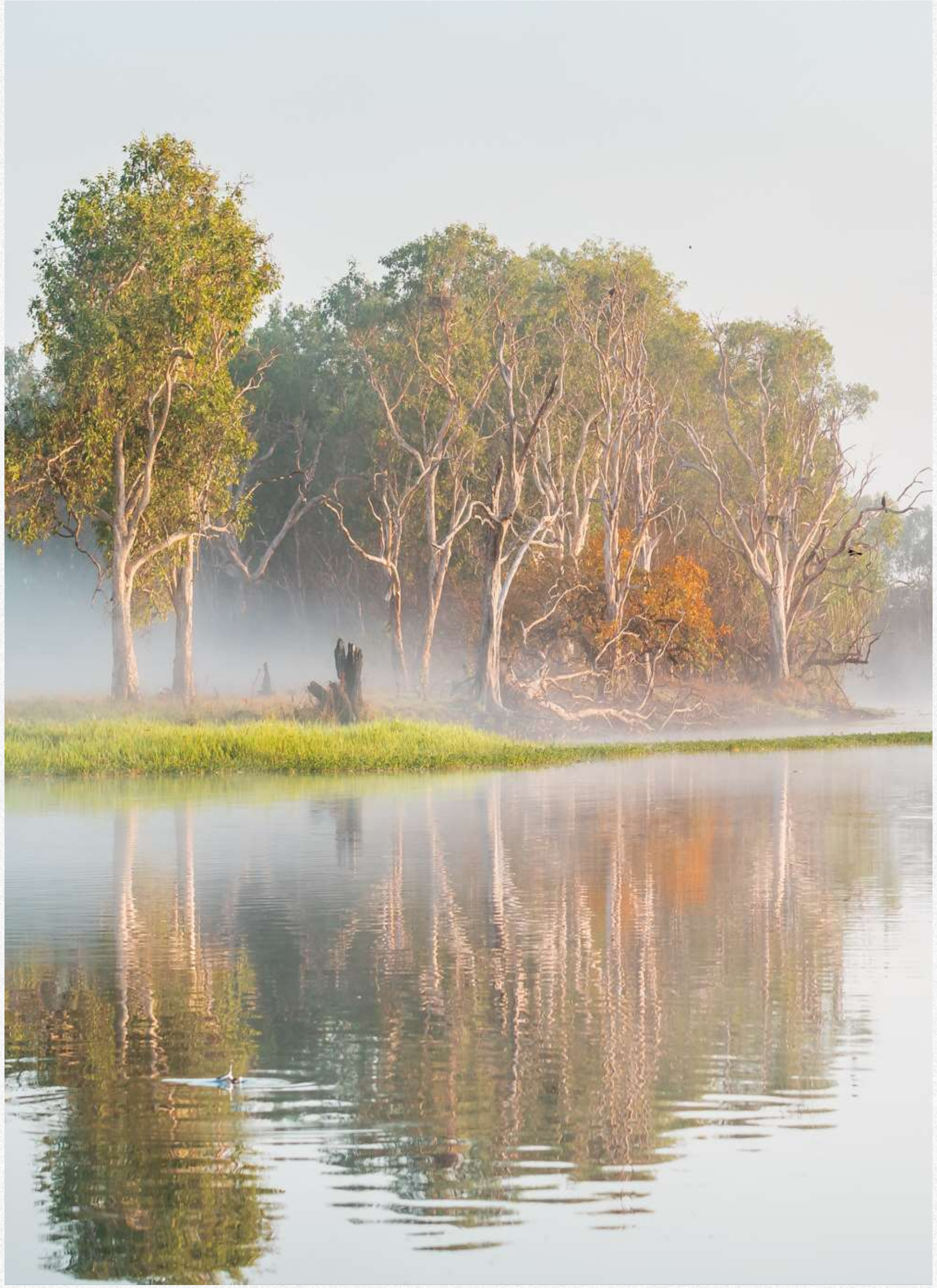
MODELLING FLOW HABITAT ECOLOGY

01: Northern Australia river and floodplain ecology

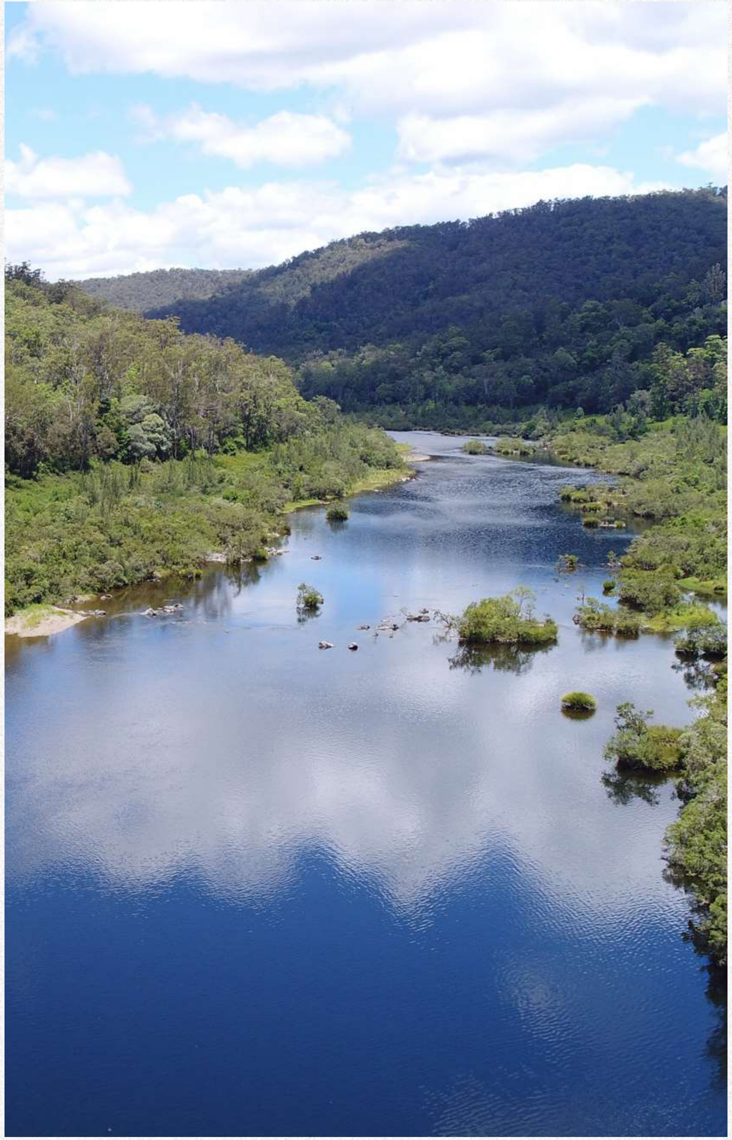
River flows are important for driving the condition and persistence of biota, to support habitats, and to facilitate ecosystem function. In the tropics of northern Australia, flow regimes are highly dynamic with strong seasonal trends. Amongst the high variability of the natural flow regime, flow regime change associated with water resource development and climate change threaten to modify the flow of these natural systems.

Despite the ecological importance of flow, quantifying the relationships between hydrological change and ecological outcomes remains a challenge. Biota interact with their physical environment differently and have differing requirements including inundation, depth, velocity and connectivity which vary across the landscape. Complex landscapes and highly variable flow regimes means that interactions between flow and geomorphology result in different hydrological and hydraulic characteristics across different settings, often making discharge alone a poor proxy for ecological outcomes in many novel settings.

This work aims to incorporate both the mechanistic understanding of biotic habitat preferences with correlations of their distributions within the landscape to model outcomes to species flow habitat suitability and other ecological functions in northern Australia and demonstrate this with a case-study in the Finniss catchment in northern Australia.



The ecology of hydrodynamics



Improvement in our conceptual understanding of ecological flow needs is increasingly indicating that ecological flow requirements have a complex relationship with geomorphology and flow dynamics through the landscape, with responses often being non-linear in relation to discharge (Theodoropoulos, 2020; Whipple, 2018). Hydrodynamic modelling provides a mechanism to which to explore ecological relationships through space and time, and to enable analysis to compare differences between scenarios in complex geomorphological settings.

Hydrology and hydraulics

The habitat and structure of aquatic environments is defined by physical processes. For a large part, this is driven by hydraulics including the *depth* and *velocity* of water. Depth and velocity influence erosion and sedimentation, turbidity, oxygenation, light penetration, temperature and vertical mixing, as well as the influencing the feeding and sheltering conditions for fauna and the ability for macrophytes to photosynthesize and hold fast in the substrate.

Inundation

Many species and their habitats require *inundation* for providing foraging and nesting habitat, and serving other functions such as providing ground water recharge or facilitating productivity. The extent and duration of inundation in dynamic systems is important for ensuring provision of adequate habitat and ecosystem functions.

Connectivity

Longitudinal and lateral *connectivity* (along the river, and out onto the floodplain respectively) enables the movement of biota and materials across the landscape. Many wetlands require lateral connection to the river for filling, and many biota use this connection to move between habitats, with nutrients exchanged across the landscape. Water depth, duration, frequency and timing of the hydrological connection is important.

Environmental covariates, distribution and extrapolation

The *distribution* of species is defined by a complex set of environmental drivers beyond flow conditions including temperature, geography, geology, climate and human modification. Many of these variables help determine the realized niche and distribution in which species occur.

The method and workflow

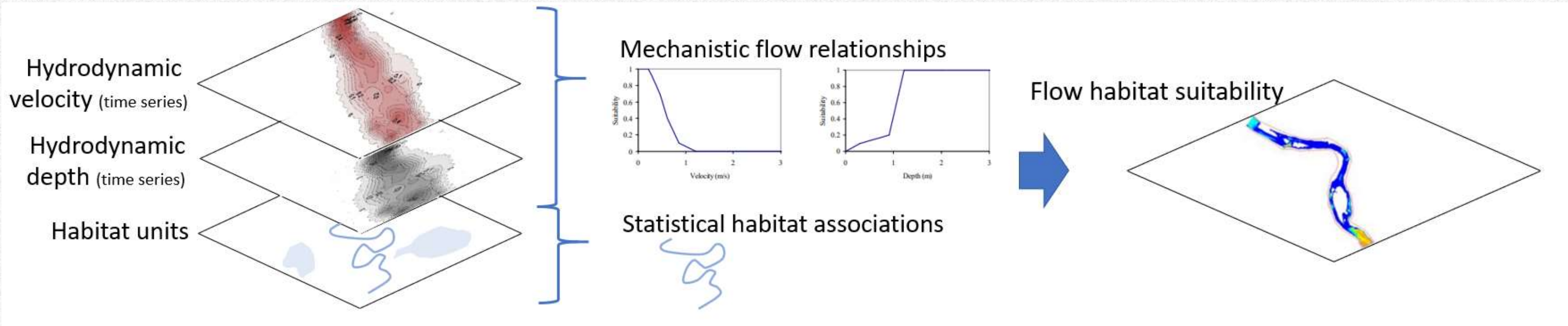
The HD habitat suitability modelling workflow has been developed as a demonstration of the scientific approach and to enable exploration of outcomes of different flow scenarios.

This work consists of several inter-related components that include:

- Hydrodynamic model
- Species distribution model
- Flow habitat preferences model
- Connectivity and persistence model*

* Work still under development pending key data inputs

Generalised conceptual overview of the flow habitat suitability model



This work gives us the capacity to bring these components together to explore a rich suite of drivers related to inundation, hydraulics, connectivity, biophysical habitat and climate for assessing changes to freshwater dependent species, habitats and functions across rivers, wetlands and floodplains in northern Australia.

Benefits and potential uses

Understanding and predicting ecological relationships

- Predict spatial and temporal habitat suitability for a range of biota in a model that represents habitat suitability considering the traits and preferences of biota.
- Extrapolate fundamental relationships across different geomorphological and flow regime templates, explore outcomes as experienced by biota rather than proxies of discharge.
- The ability to explore a range of ecological indicators including biota (e.g. fish, vegetation and waterbirds), and ecosystem functions (e.g. productivity) in a generalisable modelling workflow.
- Enable transferability of parameters between sites as knowledge is based upon physical processes and requirements.
- Incorporate mechanistic understandings of species habitat use in dynamic landscapes by identifying preferences or limiting processes.

Scenario analysis

- Explore trade-offs and risks of potential water resource development scenarios.
- Explore possible outcomes associated with climate change.
- Capture incremental effects of water management and water resource development.
- Explore range shifts associated with changed flow habitat conditions.

02: Modelling hydrodynamics - methods

The demonstration undertaken in this report was conducted using a two-dimensional regular grid hydrodynamic (HD) model (MIKE21) to provide the hydrodynamic parameters of depth, velocity and inundation. The HD model is for the middle and lower reaches of the Finniss River, with a catchment area of 9490 km^2 with 3925 km^2 being modelled. Input to the HD model includes topography, surface roughness and water level and river flow at the boundary. Surface roughness is estimated using a SRTM 30 m DEM for topography and Geoscience Australia's dynamic land cover product. At the upstream boundary (Gitchams) daily discharge was specified and hourly tide level was used at the seaside boundary.

Key model attributes:

- Pixel resolution: 60 m square grid
- Simulation time step: 5 second (collated to 4 times daily and daily timesteps)
- Simulation period: 30 days for each flood event

Output variables:

- Inundation
- Inundation depth
- Flow velocity

What we have used

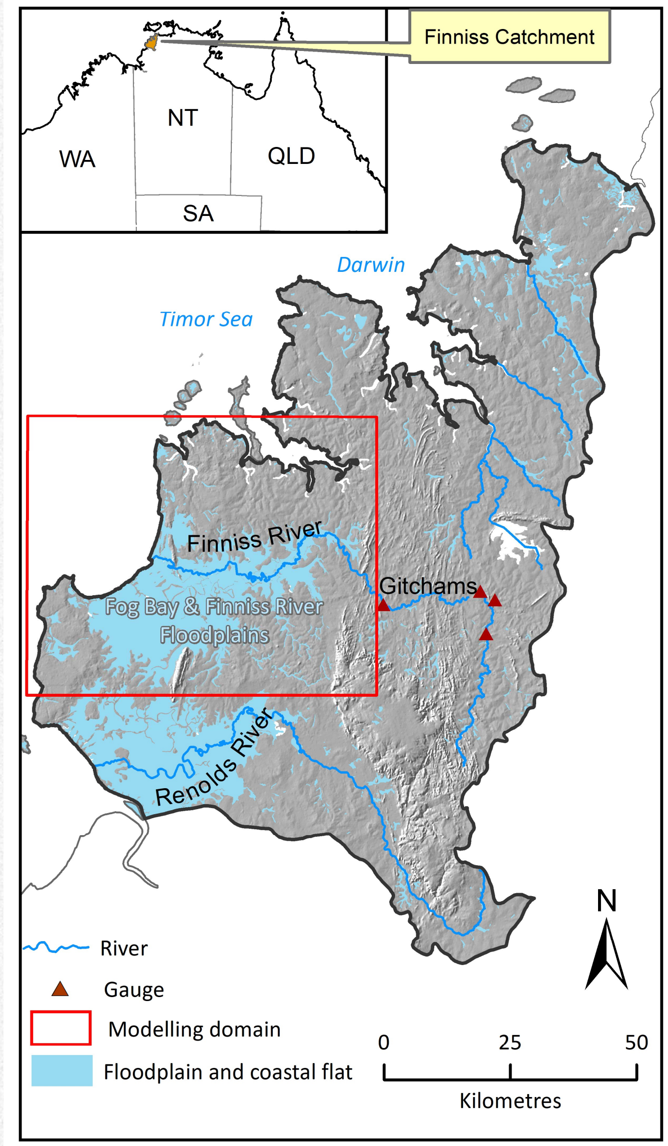
Modelled flows are used for both the Baseline and future scenario modelling.

We have used 3 flood events of different magnitudes and Annual Exceedance Probabilities (AEP) to investigate the inundation dynamics and velocity under potential changes. These are:

- AEP of 1 in 2 years with a Q_{max} of 350 m^3/s (2006 flood)
- AEP of 1 in 10 years with a Q_{max} of 701 m^3/s (2014 flood)
- AEP of 1 in 25 years with a Q_{max} of 905 m^3/s (2011 flood).

Rationale for choice

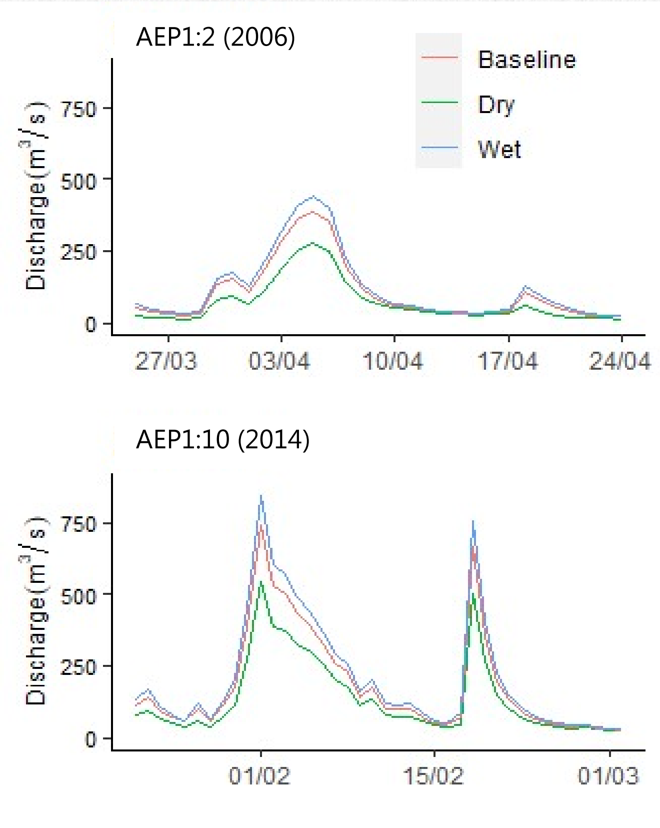
Modelled flows can be used to represent different policies (e.g. water resource development), management actions and/or climate futures. The three different flood events model hydrodynamics and change across a range of conditions.



Study area map showing Finniss floodplain and hydrodynamic modelling domain

Scenarios of change

Changes in inundation area, depth and flow velocity were modelled for the Baseline scenario as well as future climates and a dam scenario. A typical example of daily inflow is shown below for the AEP 1 in 2 (2006) and AEP 1 in 10 (2014) flood events.



Baseline scenario

The Baseline scenario represents historical climate and current development. The historical climate is defined as the climate (rainfall, temperature and potential evaporation) modelled over the three flood events.

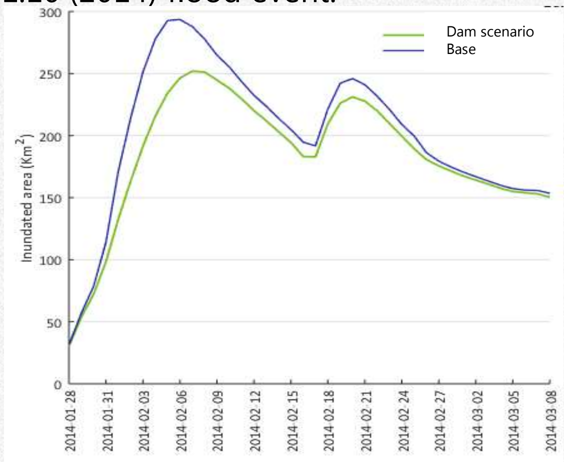
Climate scenarios

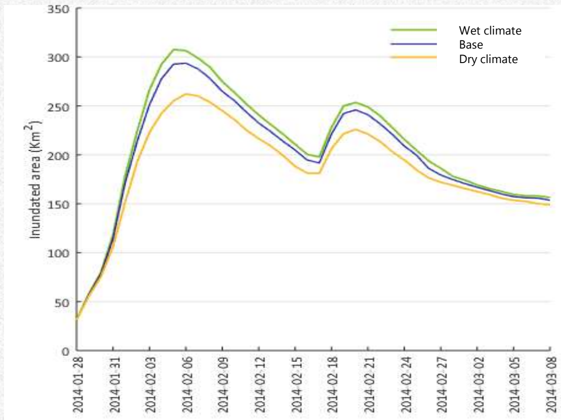
Future climate scenarios were projected using results from 32 global climate model (GCMs). To consider uncertainty in possible future climates, we have investigated 2 scenarios, wet future (wet) and dry future (dry), representing the 10th and 90th percentile of all GCM data respectively. Historical data from 1890 to 2015 were used to construct future climate and prediction were made for 2060 (average of 2046 to 2075).

As expected, inundation increases for wet climate and decreases for dry climate. For the AEP 1:10 (2014) flood, maximum inundation area increases by 5% for the wet climate but decreases by 11% for the dry climate.

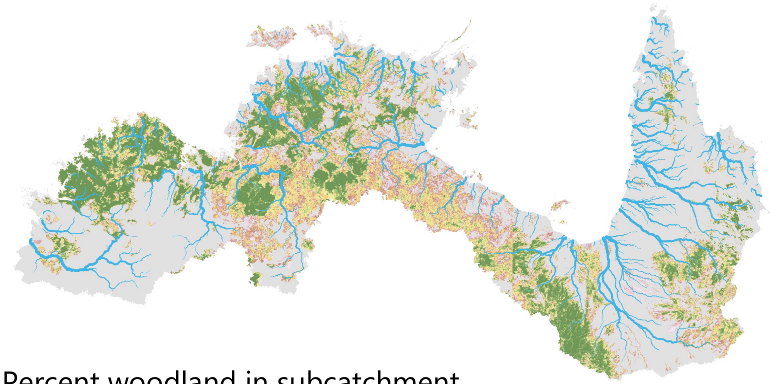
Dam scenario

For the dam scenario, a dam with capacity of 343 GL was considered at Mount Bennet on the Finniss River. The dam resulted in 14% decrease in inundation area for the AEP 1:2 (2006) flood and 8% decrease relative to the AEP 1:10 (2014) flood event.

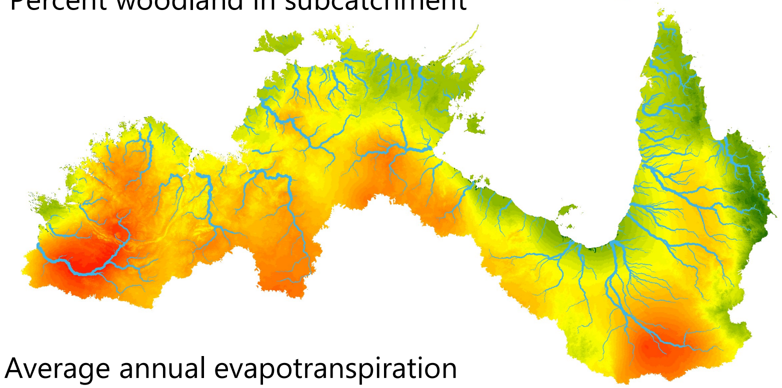




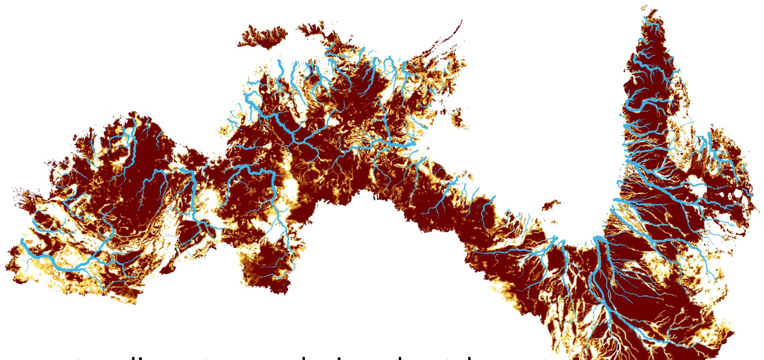
Species distribution modeling - methods



Percent woodland in subcatchment



Average annual evapotranspiration



Percent sedimentary rocks in subcatchment

Overview

The spatial modeling component was split into two parts.

1. A prototype spatial database management software that can automatically populate any spatial unit with data from raster and vector datasets
2. An automatic species distribution modeling (SDM) workflow that automatically harvests data from the Atlas of Living Australia to generate occurrence probability

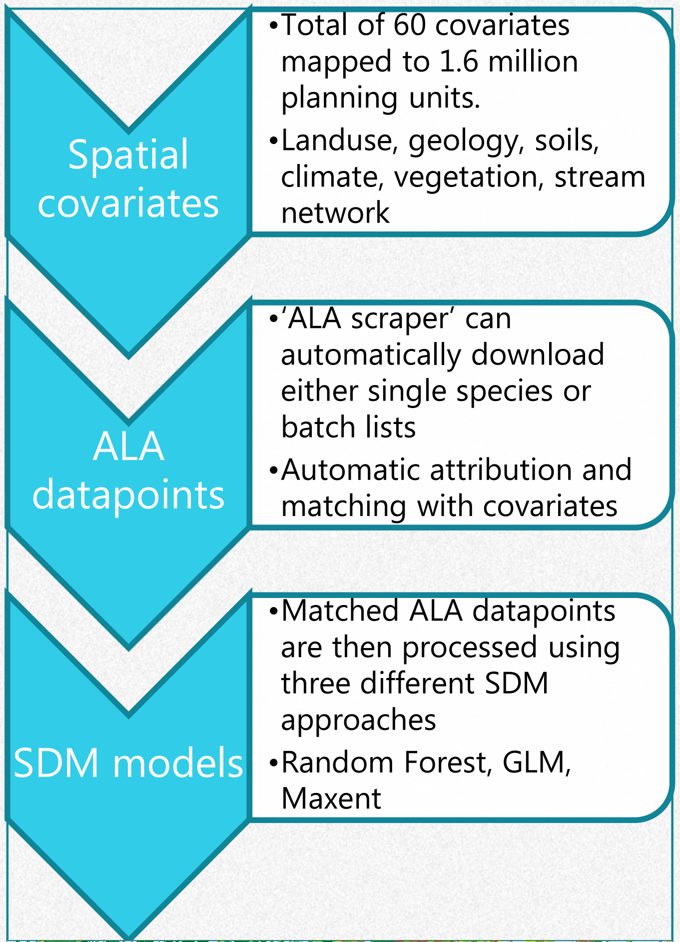
Data atlas prototype

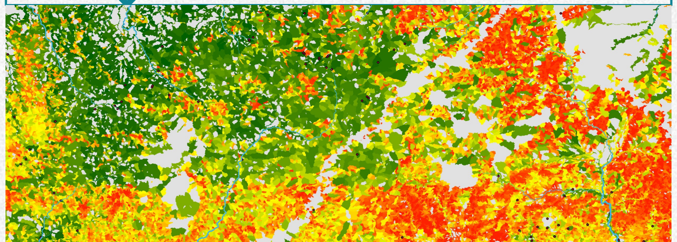
A key bottleneck to species distribution modeling was the availability of up-to-date covariates. We built infrastructure to attribute any spatial unit >1 km with existing and pre-cleaned environmental data (see spatial covariates). *This can be used for any future project in Australia.*

SDM modeling workflow

With the data atlas as a baseline, we designed a workflow that can 'scrape' data for any species from the ALA and match it automatically with the data atlas.

After downloading the data and auto-cleaning observations, the point observations are routed to three SDM algorithms. In case of successful models, the predictions are exported to both GIS shapefiles as well as raster images.





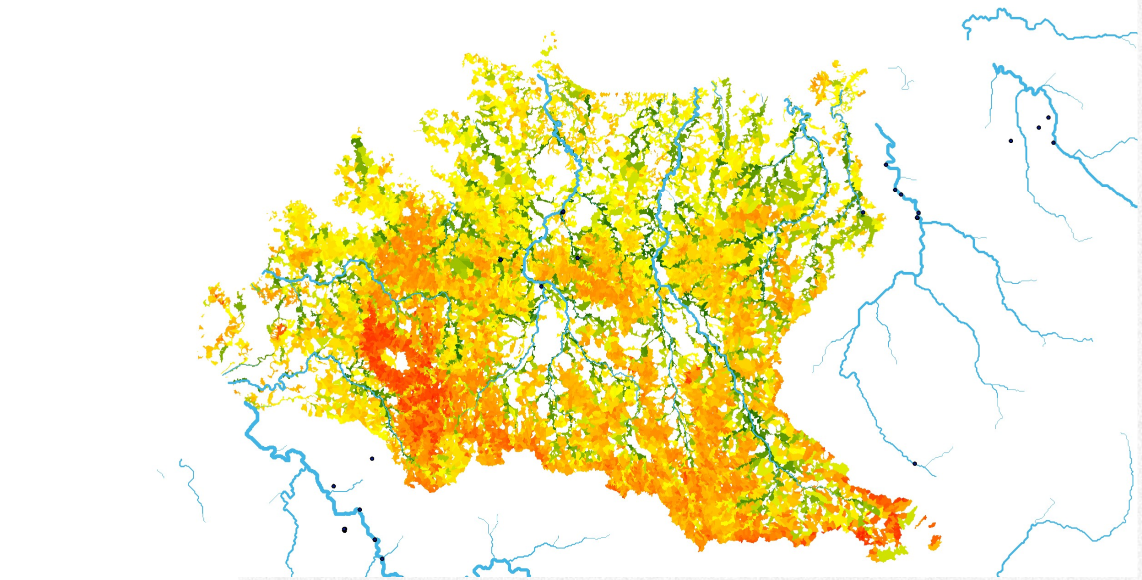
Pristis pristis (freshwater sawfish)

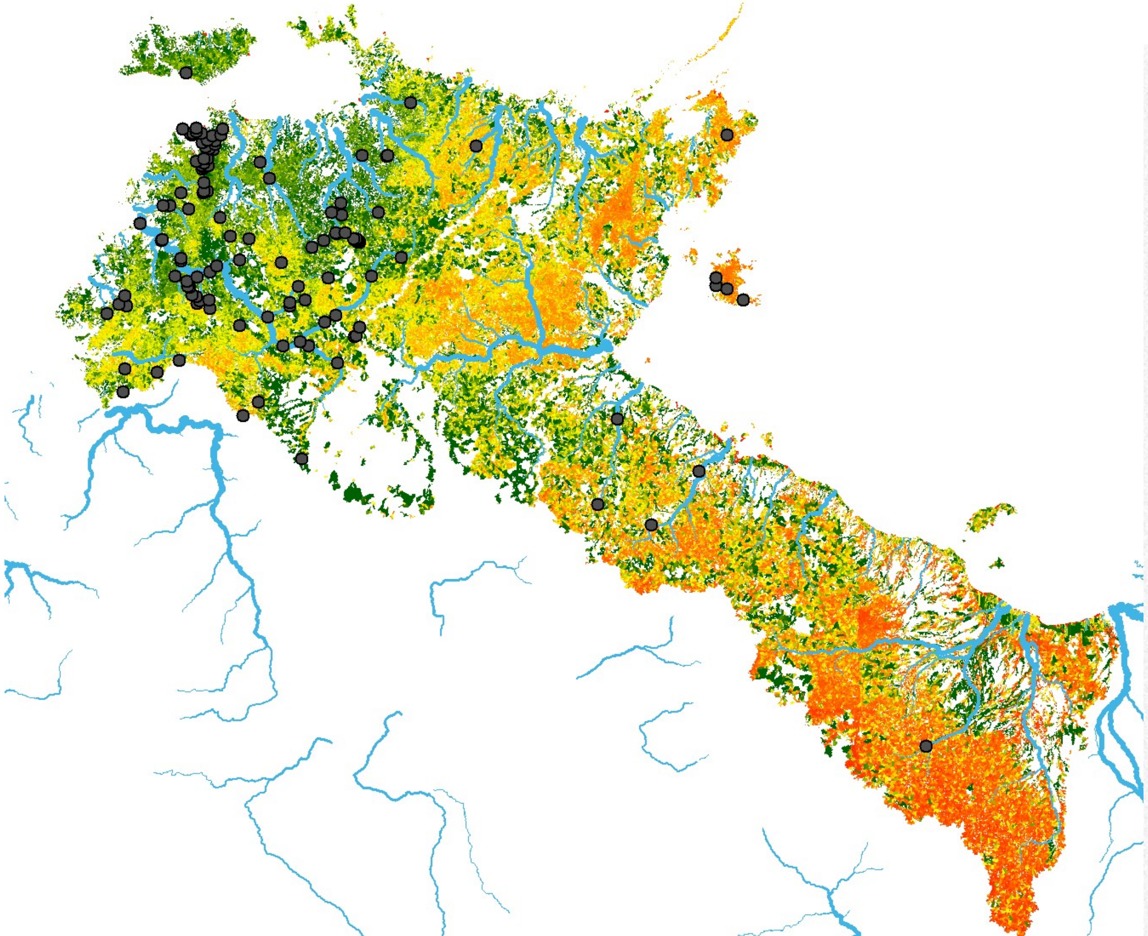
Random forest model for *Pristis pristis* (freshwater sawfish)

ROC AUC=0.9 (very good)

Key drivers:

- Distance from source
- Climate (temperature)
- %forest in the catchment





Melanotaenia australis

GLM model for *Melanotaenia australis* (rainbowfish)

ROC AUC=0.85 (good), r-sq=0.4

Key drivers:

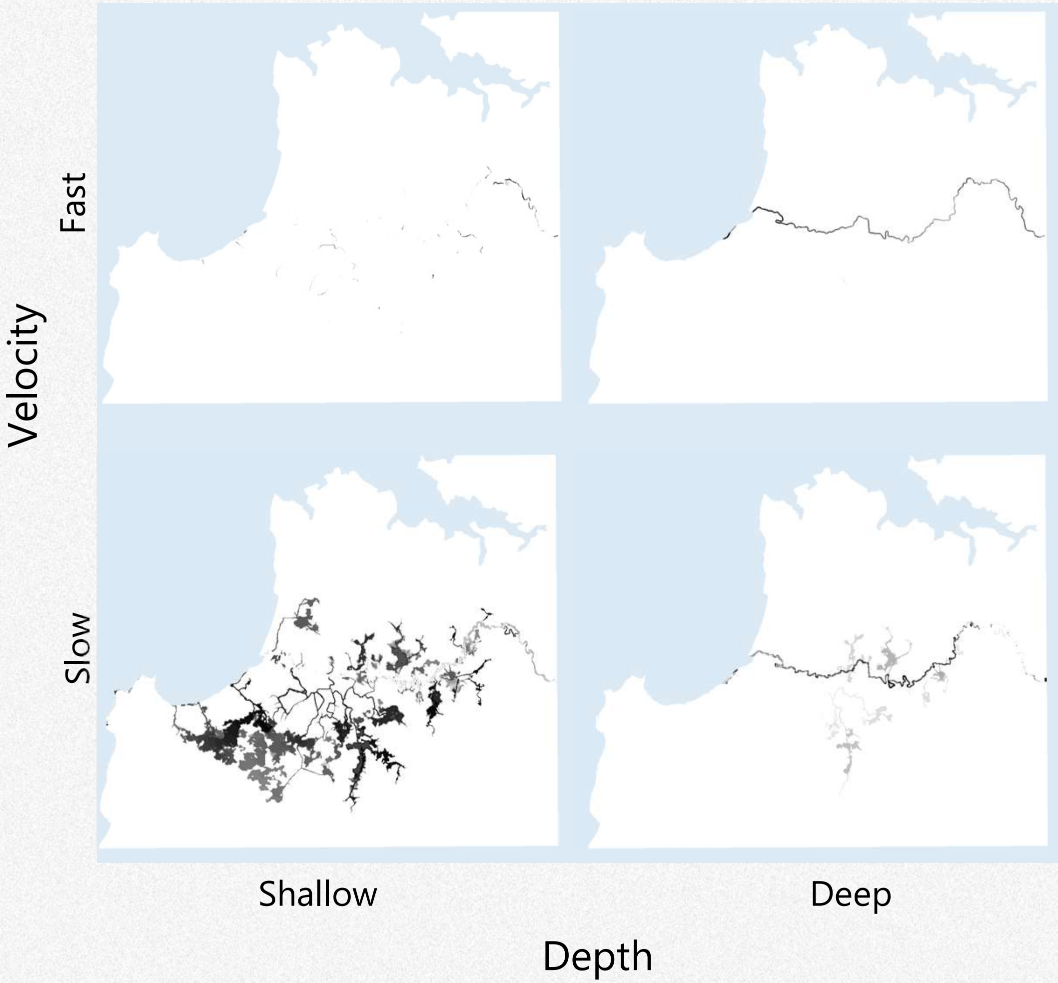
- Aridity (negative)
- Geology/soils
- %woodland in the catchment

Flow habitats - methods

Flow habitat suitability is assessed using depth and velocity outputs from the hydrodynamic models. The approach uses species or functional group specific habitat preference curves informed by literature and/or data to provide mechanistic links between hydraulic variables from HD modelling to predict habitat suitability. The form of these relationships can be used for a range of biota such as fish and waterbirds where depth and velocity are important determinants of habitat suitability. This approach can also be adapted to model Gross Primary Productivity given change in carbon production in different habitats as a result of changes in inundation extent, depth and velocity.

Model results are at daily timesteps with 60x60m resolution across the spatial domain of the hydrodynamic model (variable by HD model output- see page 9 for this demonstration) showing the suitability of habitat from a scale of 0 (not suitable) to 1 (preferred) for a species or functional group considering both depth and velocity at each grid cell.

Model outputs show the spatial-temporal flow habitat suitability for species or functional groups across the landscape at each model timestep. Results can be quantified and aggregated across time periods, and compared between scenarios to identify the loss or addition of weighted habitat suitability between scenarios.



Time averaged distribution of idealised hypothetical habitat occurrences across the Finniss catchment through a 1 in 10 year flood event (AEP1:10 Base-2014). Deep habitat is >2m and fast habitat has >0.4m/s water velocity. Note these are not representing species based models and that habitat state changes through the time period depending upon conditions (shown is the average across this time period).

Waterbird habitat suitability - methods

Wetlands throughout Australia are home to a wide range of waterbird species. Waterbirds are highly dependent on the resources provided by these wetlands, including for food, shelter and nesting, all of which are critical for species survival and population maintenance.

Hydrological regimes are fundamental to sustaining the ecological characteristics of wetlands (Pettit et al., 2017). The timing, duration, extent and magnitude of the flooding of wetlands has the greatest impact on the ecological values, including species diversity, productivity and habitat structure (Close et al., 2015).

Here we look at one aspect of this hydrological regime, magnitude, specifically depth and extent, to predict the suitability of floodplain wetlands for a functional group of waterbirds, the colonial and semi-colonial nesting wading waterbirds.

Modelling suitable habitat

Using the depth outputs from the hydrodynamic model (see pages 9-10), a biologically meaningful depth threshold was selected. For the colonial and semi-colonial nesting wading waterbirds functional group, a value of 0.1 m was used. The outputs from the model were reclassified using this threshold, and the area at each timestep was calculated, for each of six scenarios. The maximum extent for each of the scenarios was determined and the percentage difference from the baseline scenario was calculated. This was completed for an AEP 1:2 and an AEP 1:10.

Colonial and semi-colonial nesting wading waterbirds

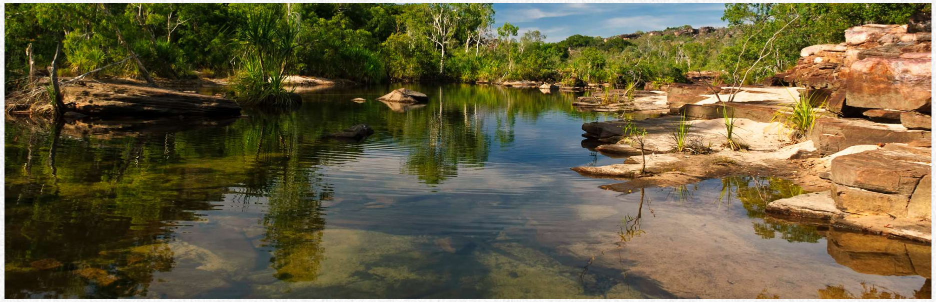
The colonial and semi-colonial nesting wading waterbirds is a functional group that includes waterbird species that have a high level of dependence on water for breeding, including flood timing, extent, duration, depth, vegetation type and vegetation condition. These species nest in large colonies and prefer shallow water with medium to low-density vegetation for foraging (Garnett et al., 2015). This group includes ibis, spoonbills, herons, egrets, avocets, stilts, storks, and cranes.

Glossy Ibis (*Plegadis falcinellus*)

03: Fish flow habitat suitability - demonstration

Freshwater fish species have strong associations with physical habitat variables. In rivers and streams, these operate, and can vary across scales of both space and time. Studies across a range of species nationally and internationally have revealed that two of the most important habitat variables for fish are often identified as water depth and velocity (Aadland 1993; Keller et al 2019). Changes in these physical habitat variables can influence species composition, distribution and abundances, driven by differences in foraging, spawning and refuge needs between species (Keller et al 2019).

In northern Australia, the seasonal dynamics of the flow regime are significant. Our understanding of the possible ecological impacts of water resource development and climate induced changes in flow is limited, however, there is concern that changes in flow regimes will change the availability of species preferred habitats within affected catchments. Improving our ability to estimate any incremental changes resulting from flow regime change is important for ensuring sustainable development in northern Australia.

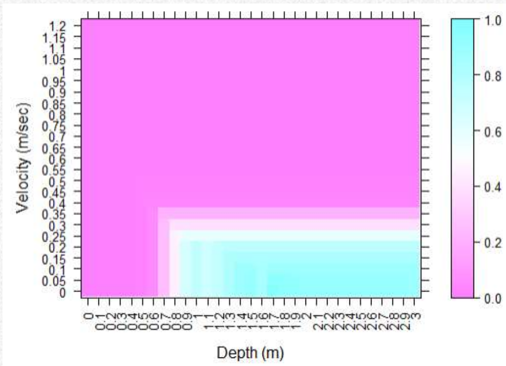


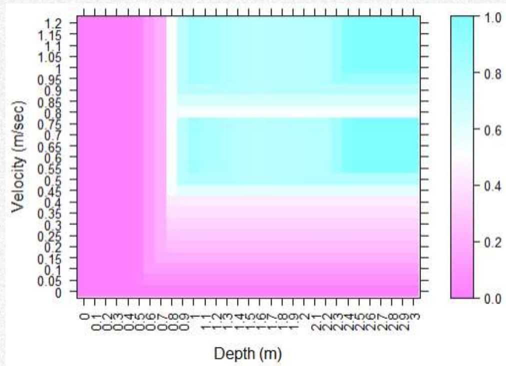
Rainbowfish

Rainbowfish (*Melanotaenia australis* and others) are a group of small freshwater fish that are found across large parts of northern Australia. Habitat associations include streams, swamps and lagoons, and where occurring in rivers, they prefer slower flowing backwaters and shorelines (Bray et al 2020; Tappin 2013). The habitat preference for this species can be described as 'slow moving and deep' water.

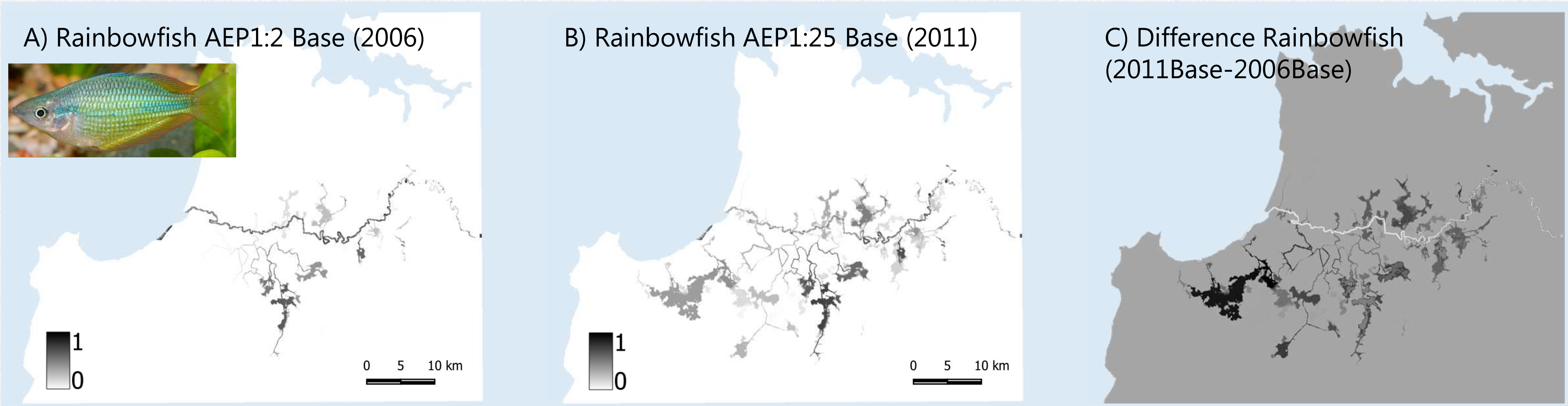
Diamond mullet

Diamond mullet (*Planiliza ordensis*) also known as the Ord River mullet, lives in both brackish and freshwater habitats of northern Australia. This species is often found hundreds of kilometers into freshwater systems (WoRMS 2022; Pascualita and Bailly). The freshwater habitat preference for this species can be described as 'fast moving and deep' water.

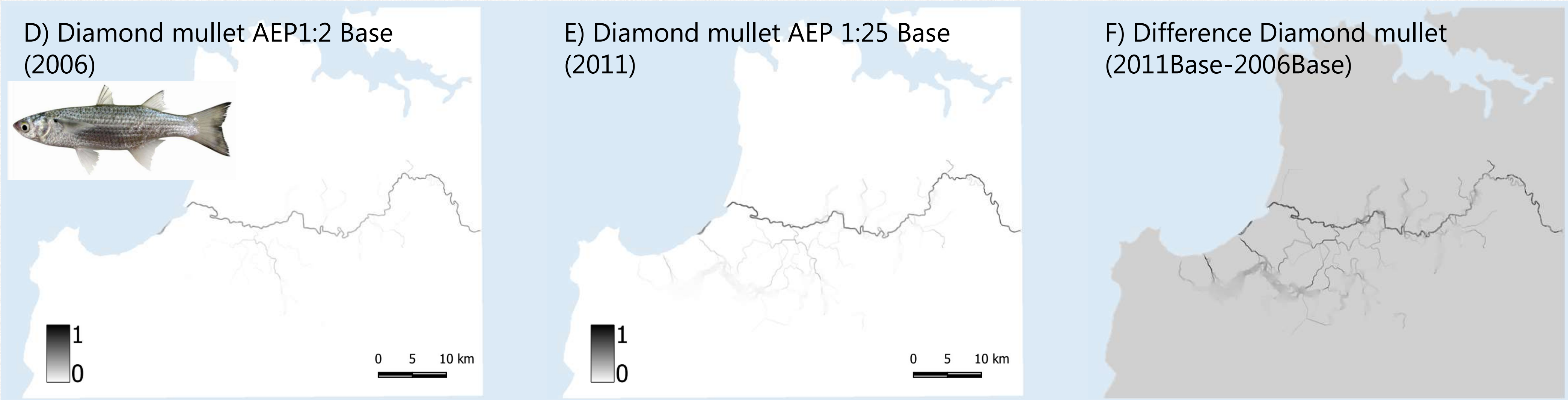




Flow habitat preferences for Rainbowfish (left) and Diamond mullet (right) adapted from Keller et al (2019)



Rainbowfish habitat preference modelling indicated suitable habitat commences in the river channel, then transitions onto the floodplain during the flood pulse for both the small (A AEP1:2) and large (B AEP1:25) flood events. However, the larger 1 in 25 year flood event in 2011 (B) inundates greater areas of the floodplain, thereby providing significantly more suitable habitat. During the larger flood event, habitat within the habitat of the river channel is, on average across the time period, less suitable compared to the smaller 1 in 2 year event (indicated by the white sections along the main river channel in Figure C) largely due to changes in velocity associated with the higher flows.



Diamon mullet flow habitat modelling shows preferred habitat restricted to the main river channel during the small flood event (D AEP1:2), and marginally extending into some of the larger flood runners during the larger flood event (E AEP1:25). The larger flood event shows only a marginal increase in flow habitat suitability associated with the larger flood runners compared to the smaller event (indicated by the darker shading in Figure F).

Waterbird habitat suitability - demonstration

The results of this study show that the future wet climate is the most favourable scenario for the colonial and semi-colonial nesting wading waterbirds (an increase of 6.2% and 4.8% for the AEP 1:2 and AEP 1:10 respectively, when compared to the current climate baseline scenario). The least favourable habitat is the future climate dry, dam scenario (a decrease of 42.9% and 32.2% for the AEP 1:2 and AEP 1:10 respectively, when compared to the current climate baseline scenario).

Waterbird species in the colonial and semi-colonial nesting waders functional group are sensitive to changes in the depth, extent and duration of shallow wetland environments, particularly during nesting events, which can have a significant impacts on nesting, nest success, juvenile recruitment and adult survival.

River regulation, including the construction of dams, and climate change, are two recognised threats to waterbirds (Kingsford et al., 2013). Dams can prevent water from flowing onto floodplain wetlands by capturing water from large rainfall events, preventing flood pulses from moving down the channel (Kingsford, 2000). A change in the climate may affect rainfall, runoff and evapotranspiration patterns (Grieger et al., 2020; Salimi et al., 2021), impacting on the hydrology of a system, including the base flow and flood patterns (Erwin, 2009). This loss of connectivity to the floodplain can result in the reduction of wetland area, and even loss of wetlands, as they transition into terrestrial habitats.

Area of suitability habitat in the Finniss catchment for colonial nesting waterbirds using a depth threshold of 0.1 m for (a) AEP 1:2 and (b) AEP 1:10. Percent difference is relative to the current climate scenario.

(a) AEP 1:2

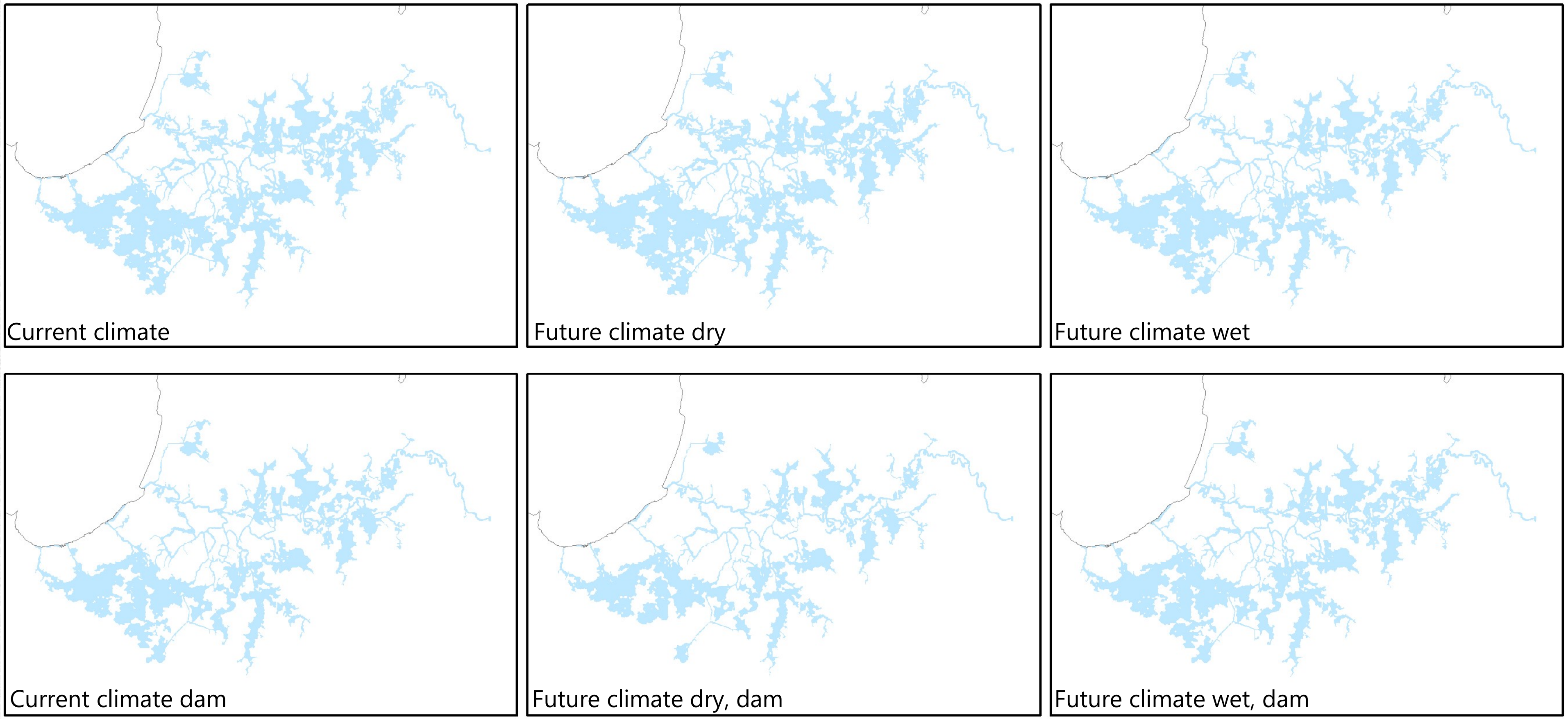
	Area (km^2)	% difference
Current climate	179.8	NA
Future climate dry	154.2	14.2
Future climate wet	191.0	-6.2
Current climate dam	136.4	24.1
Future climate dry, dam	121.2	42.9
Future climate wet, dam	149.9	21.9

(b) AEP 1:10

	Area (km^2)	% difference
Current climate	314.5	NA
Future climate dry	280.1	10.9
Future climate wet	329.5	-4.8
Current climate dam	270.1	14.1
Future climate dry, dam	227.5	32.2
Future climate wet, dam	287.0	10.2

NA = not applicable

Royal spoonbill (*Platalea regia*), an example of a colonial and semi-colonial nesting wading waterbird.



Habitat suitability in the Finniss catchment for colonial and semi-colonial nesting wading waterbirds using a depth threshold of 0.1 m for six different flow scenarios with an AEP 1:10. The future climate dry, dam scenario had the smallest area of suitable habitat when compared to the other scenarios.

Productivity - demonstration

Gross primary production (GPP) describes the rate of generation of carbon by autotrophs and is a primary control of food web dynamics. Seasonal inundation is an important regulator of aquatic GPP in many tropical river systems (Davies et al., 2008; Junk et al., 1989). Seasonal changes to connectivity between rivers and floodplain wetlands in the wet-dry tropics are significant, with inundated area increasing substantially during the wet season (Hunt et al., 2012).

Aquatic carbon flux in tropical streams is a fundamental consideration in the assessment of possible impacts of climate change and future development (Garcia et al., 2015). However, patterns of GPP can be confounded by covariate drivers, (e.g., macrophyte shading, turbidity, temperature, hydraulics etc.) and dynamic patterns of riverine and wetland GPP are poorly understood.

The productivity model based upon the 'Flow-habitat' method (page 13) incorporates separate river and floodplain GPP models to estimate productivity across these very different habitats.

Wetlands and floodplains

Tropical floodplains are recognised as being one of the most productive ecosystems on earth. Seasonally inundated floodplains typically have the highest rates of production in tropical river systems, with ephemeral wetlands recognised as being particularly dynamic (Beringer et al., 2013).

For catchments, increased wetted surface area is likely to increase total GPP disproportionately, since many seasonally inundated wetlands are shallow, with a higher proportion of the water column occurring in the photic zone than in adjacent rivers (e.g., providing a large potential for generation of aquatic carbon).

Maximum GPP in *wetlands* is modelled as 1.5 mg C m-2 day-1 with declines to 0.15 mg C m-2 day-1 with high water depths.

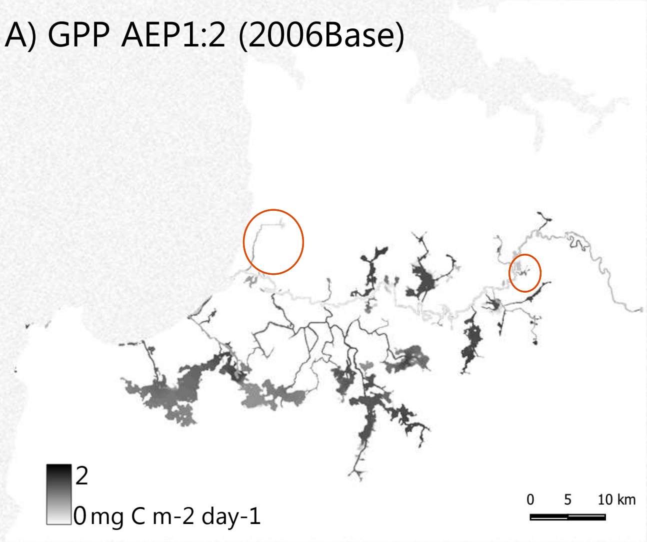
Rivers and streams

Gross primary production in the channels of tropical rivers is performed by epiphytic and benthic algae on surfaces (e.g., benches, snags, rocks, macrophytes etc.), planktonic algae in the water column and by submerged macrophytes.

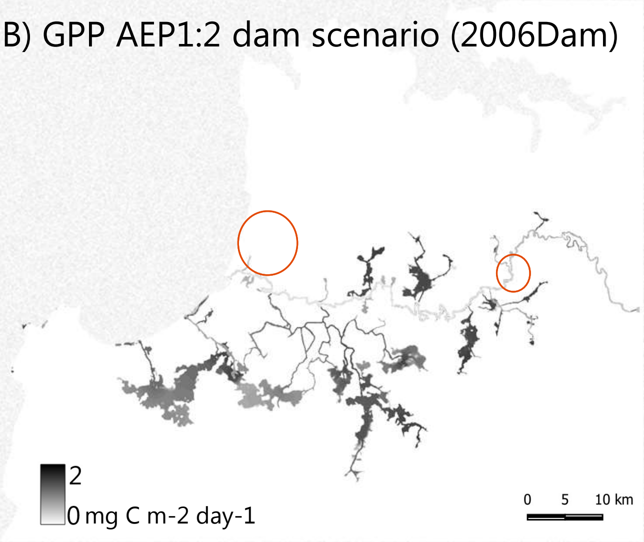
In tropical rivers, seasonally dynamic water discharge resulting in highly variable river levels and high water velocity can limit the extent of aquatic macrophytes (Davies et al., 2008, Hunt et al., 2012). Additionally, during large wet season flows, sediment disturbance and altered benthic habitats result in high turbidity and limit the production of benthic periphyton and planktonic algae in many tropical streams (Garcia et al., 2015)

GPP in *rivers* commences at 0.7875 mg C m-2 day-1 on wetted surfaces and declines to 0.08 mg C m-2 day-1 under both high flow and depths.

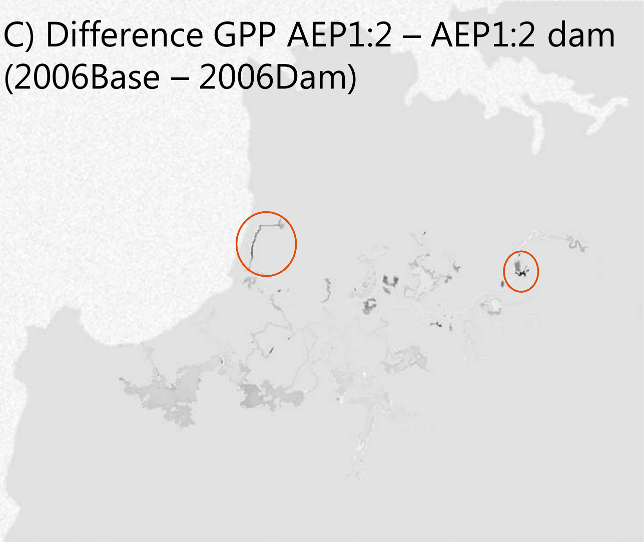
A) GPP AEP1:2 (2006Base)



B) GPP AEP1:2 dam scenario (2006Dam)



C) Difference GPP AEP1:2 – AEP1:2 dam (2006Base – 2006Dam)

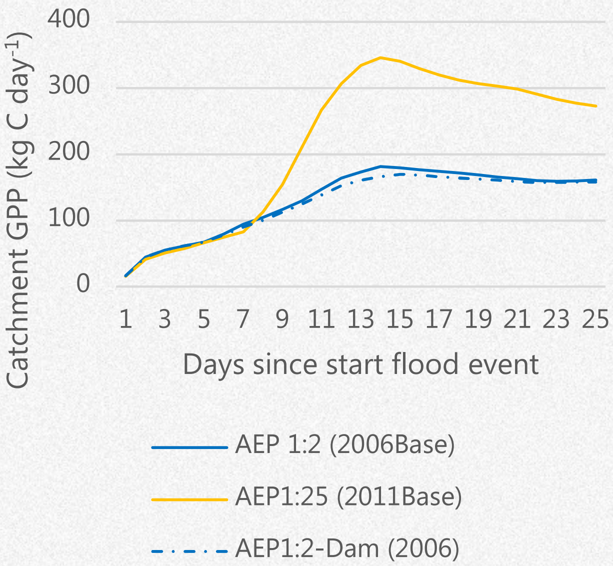


A) GPP in the AEP 1:2 (2006) Base scenario flood event showing higher levels of production in wetlands compared to the river channel. GPP primarily associated with inundated wetlands.

B) GPP in the AEP 1:2 (2006) scenario with dam simulation. Small reductions in GPP are associated with areas under reduced inundation (circled red).

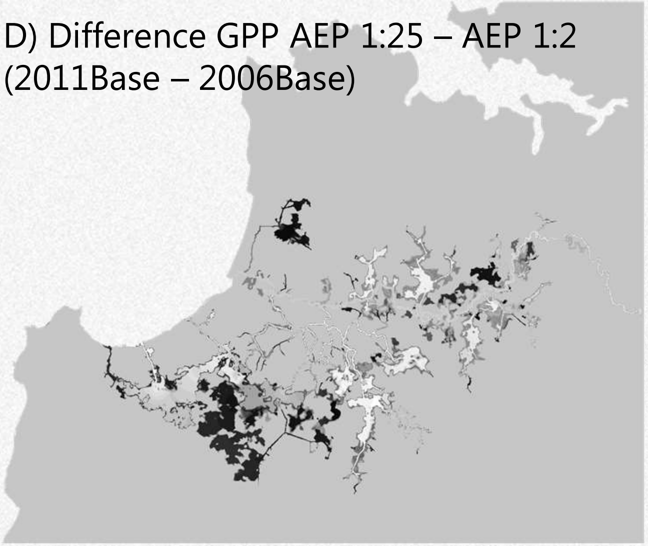
C) Difference in GPP between the AEP 1:2 (2006) Baseline and dam scenarios. Dark areas show areas of higher GPP in the base scenario compared to the dam scenario, while lighter areas show decreases in production with only marginal differences

D) Difference in GPP between the AEP 1:2 (2006) Baseline and AEP 1:25 (2011) Baseline (not separately shown) scenarios. Dark areas show areas of higher GPP in the AEP 1:25 Base scenario compared to the AEP 1:2 Base scenario, while lighter areas show decreases in production.



Time series of GPP under the AEP 1:2 baseline, AEP 1:2 Dam and AEP 1:25 Baseline scenarios

D) Difference GPP AEP 1:25 – AEP 1:2 (2011Base – 2006Base)



04: Method assumptions and limitations

All material and results within are provided as a demonstration of methods. Work is ongoing to refine and ensure robustness of methods across a range of different situations including different locations and flow scenarios, and for different species and to verify outputs.

Component	Assumptions/limitations and caveats
Flow-habitat	Different drivers may operate at different scales, e.g. microhabitat for sheltering or feeding may be present but not reflected within the current scale of analysis.
Flow-habitat	Flow preference relationships may not hold across a broad range of conditions or seasons, or across different times of the day. Further work is required to understand seasonal or other difference in preferences.
Flow-habitat	Different habitats may be required across a year or at different life-stages that are not accounted for in the analysis. There may be different limitations and drivers that are not accounted for in habitat preference modelling. Timing of analysis may not associate with times of habitat use (e.g. life-history in some species).
Flow-habitat	That habitat preference where related to a limiting factor for the species will result in changes to the species abundance, distribution or condition if the habitat suitability changes.
Flow-habitat	Drivers beyond flow influence suitability of habitat.
Flow-habitat	Habitat suitability may not be associated with presence of the species/functional group.
SDMs	Currently largely untested and especially in case of RF models prone to overfitting. Proper tests will be run in the next NAWRA phase.
SDMs	More predictor variables will be included in Atlas 2.0.
SDMs	Optimal ALA setting will be tested in the next NAWRA phase.
Waterbird habitat suitability	Drivers beyond water depth influence the suitability of habitat for waterbirds.

Further information

Links to other work

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Further information

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