# An assessment of risks to aquatic ecosystems in northern Australia from development and sea level rise threats

## Final report for NAWFA - Chapter 4

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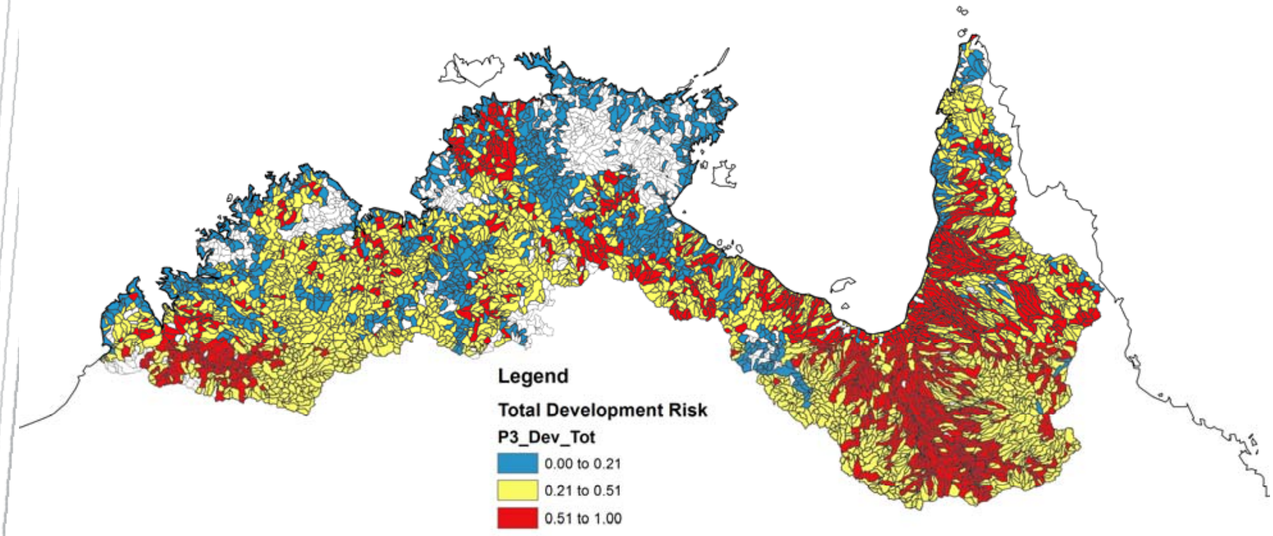


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# SUMMARY


1. Risks to aquatic ecosystems and HCVAE assets from Development in 2010, and a projected 1m Sea Level Rise (SLR) in 2100, were assessed across the NAWFA study area basin (53 AWRC basins) and sub-catchment levels (6,393). Fifteen basins were selected by NT, Qld and WA government jurisdictions for focus and their risk results are highlighted throughout this report. Detailed assessments were undertaken also for the Norman River, South Alligator River and Finniss River basins.
2. Aquatic ecosystems were defined as Riverine, Palustrine or Lacustrine environments, and HCVAE assets were identified as those sub-catchments that met one or more of the Framework Criteria at the 99th percentile (HCVAE99, Kennard 2010). Development risk was defined using the River Disturbance Index (RDI) model of Stein et al. (2002), an amalgamation of two other disturbance indices, the Catchment Disturbance Index (CDI) and the Flow Regime Disturbance Index (FRDI). Areas at risk from a 1m Sea Level Rise (SLR) were estimated from the NASA SRTM 1 second smoothed DEM.
3. All risk assessments at all reporting scales used a revised version of the spatially-explicit Relative Risk Model (RRM) developed for the TRIAP project by Bartolo et al. (2012) and updated in section 1 of this Chapter. The model was revised to encompass high resolution sub-catchment and species biodiversity data used in a previous NAWFA project by Kennard (2010). Additionally, the revised RRM is quantitatively based using standard exposure-effect risk probabilities (c.f. ranks), allowing risk profiles to be developed and, hence, uncertainty and sensitivity analyses to be undertaken.
4. The overall risk to aquatic ecosystems from Development in 2010 is about five times greater than that from a projected 1m SLR in 2100 (0.39 cf. 0.08, respectively), despite the large variation between basins (0 – 0.93). The combined risk is estimated at 0.45 (45%). Basins with aquatic ecosystems most at risk from current Development risks comprised clusters in the southern GoC (Qld) and the Adelaide River basin close to Darwin (NT). In contrast, basins at least risk from current Development comprise clusters in remote Arnhem Land (NT), the South and East Alligator River basins in Kakadu National Park, and the Moyle River basin far from anywhere. The basin most at risk from SLR is Mornington Inlet, being a small low-lying coastal catchment in the southern GoC.
5. The overall risk from Development to HCVAE99 assets (sum of all criteria met at the 99th percentile) was 23 time greater than a projected 1m SLR risk in 2100 (0.0045 cf. 0.0002), with the combined risk being very small (< 0.005 or < 0.5%). The Adelaide River basin had the greatest Development risk to HCVAE99 assets, followed by the adjacent Mary River basin (0.06 & 0.03, respectively). The Mornington Inlet basin had the highest SLR risk to HCVAE99 assets (0.002 0r 0.2%), although all these values are too small for meaningful comparisons.
6. The South Alligator River (SAR) and Norman River basins were chosen to compare risks at a finer scale because of their contrasting land use, reflecting a high value conservation area (Kakadu National Park) and an area encompassing intensive land use and associated catchment disturbance, respectively. Aquatic ecosystems in the Norman River basin are 19 times more at risk from Development than those in the SAR basin (0.50 cf. 0.03) and, in contrast, those in the SAR basin are four times more at risk from SLR. The risk to HCVAE99 assets from Development in the Norman River basin is twice that of the SAR

basin (0.013 cf. 0.008). In contrast, SLR risk is 13 times greater in the SAR basin than the Norman River basin (0.026 cf. 0.002).

7. The two approaches to the RRM presented in this Chapter use very different risk assessment pathways and endpoints. Hence, the results for three high level risk assessment endpoints were compared in the Finniss River basin in order to check the validity of combining outputs from both. Results were similar, suggesting that the two approaches are complementary given that they each have different advantages and limitations.

8. An analysis of risk to biodiversity from a projected 1m SLR was undertaken using the predicted occurrences of turtles, fish and waterbirds as surrogates for total biodiversity. The level of risk in coastal sub-catchments was estimated from the areal intersection between a projected 1m SLR and predicted species occurrences using the presence-only Habitat Suitability Models developed by Kennard (2010). About 10% of sub-catchments where at least one species of turtle is predicted to occur will be affected by a 1m SLR, and that for fish and waterbirds, 18%. The mean risk to waterbird species is about three times greater than that for both turtles and fish (0.70 cf. 0.21).

9. The overall results reported here are consistent with current knowledge of risks to aquatic ecosystems in northern Australia (Kennard 2010, Kennard et al. 2010b, Pusey & Kennard 2010, NALWTF 2009, CSIRO 2009, Bartolo et al. 2008, van Dam et al. 2008); basically there were no surprises. Additionally, our quantitative risk assessment results are reported within a consistent, transparent and robust framework.

10. A Bayesian Belief Network (BBN) was constructed to integrate and communicate all spatial risk assessment, and can be used at any reporting scale (e.g. across northern Australia or by basin and sub-catchment). Users can choose one of two reference time frames, 2010 (recent) or 2100 (future), and a projected percentage increase in current Development. The BBN was designed to undertake "what if" scenario simulations and, hence, may be a useful Decision Support Tool for catchment managers.

11. We recommend that, as an essential "next step" in the risk assessment process, the results reported here be incorporated into an adaptive Management Strategy Evaluation (MSE) framework to facilitate integrated assessments of future Development and Climate Change scenarios. This should be a participatory process with all NAWFA stakeholders in order to facilitate uptake and impact of research findings.

# 1. INTRODUCTION

The Northern Australia Water Futures Assessment (NAWFA) is a five year multidisciplinary program being jointly delivered by the National Water Commission (the Commission) through the Department of Sustainability, Environment, Water, Populations and Communities (DSEWPaC). The overarching objective of the NAWFA is to create an enduring Knowledge Base that provides essential information on the water resources in the northern Australia landscape and the watering needs of key ecosystem, community and cultural assets. The assessment will bring together existing information sets and commission new work where a clear need for additional information exists (see http://www.environment.gov.au/water/policy-programs/northern-australia/index.html).

The NAWFA is comprised of four components: the Water Resources program; the Ecological program; the Cultural and Social program; and, the Knowledge Base program. This project falls under the Ecological Program, which seeks to understand the key aquatic ecological assets across northern Australia (the Assets) and to gain an understanding of the risks to the values of those assets arising from changes in the hydrological regime.

The overall objective of this NAWFA project is to gain a comprehensive understanding of the likely impacts (including cumulative) of possible development and climate change on the northern Australia key ecological Assets, as identified by the Ecological Working Group and the Northern Australia Aquatic Ecological Assets Project.

## 1.1 Background – previous assessments

The risk assessment reported here draws on methodologies and data from the following previous water resource projects in northern Australia (Table 1). This current project is referred to as NAWFA2.

Table 1. Summary of previous water resource projects undertaken in northern Australia.

| Related Project | Relationship to this project |
|---|---|
| *The Wild Rivers Project* (Stein et al. 1998, 2001, 2002). | Provides catchment & flow regime disturbance indices (updated in 2010 as part of NAWFA1) as overall surrogates of development threats (to both NAWFA1 & NAWFA2, see below). |
| *Northern Australia Aquatic Ecological Assets Project* – NAWFA, Griffith University (Kennard 2010, 2011). | Will inform asset and threat selection for this project and provides relevant GIS layers to the project on the distribution of aquatic ecosystem types, freshwater-dependent species and indices of river disturbances due to catchment land use land water development within catchments. This project is referred to as NAWFA1. |
| Northern Australia Sustainable Yields (NASY) Study (CSIRO 2009). | Will inform possible climate scenarios as a result of climate change (not related to sea level projections). |
| Tropical Rivers and Inventory and Assessment Project (TRIAP). 2006. | Provides an assessment of the major pressures on aquatic ecosystems and the spatially-explicit Relative Risk Model (RRM, Bartolo et al. 2012) |
| Northern Australia Land and Water Taskforce Science Review (NALWTF 2009). | Outlines the development likely to occur in northern Australia. Chapter 3, *Aquatic ecosystems of northern Australia,* provides information on the values of, and threats facing aquatic ecosystems in northern Australia. |

*Definition of terms used in NAWFA1*

The main assets and threats data layers for the risk assessments reported here were derived as part of the previous NAWFA1 project "*Northern Australia Aquatic Ecological Assets*" (Kennard 2010, 2011). Hence, a summary of definition of terms used in that project is outlined below.

Aquatic ecosystems are defined as those that depend on flows, or periodic or sustained inundation/waterlogging, for their ecological integrity (e.g. wetlands, rivers, karst & other groundwater dependent ecosystems, saltmarshes & estuaries), but do not generally include marine waters (Auricht, 2010). This definition excluded artificial waterbodies such as sewage treatment ponds, canals and impoundments.

Hydrosystems are defined as large 'organising entities' designed to represent the variety of aquatic ecosystem types (e.g. estuaries, rivers, lakes, palustrine wetlands). The draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht 2010) now refers to hydrosystems as 'aquatic systems'.

An Ecotope is defined as the smallest ecologically distinct features in a landscape classification scheme (e.g. a 'type' of lacustrine hydrosystem). The draft Australian National Aquatic Ecosystem (ANAE) classification scheme (Auricht, 2010) now refers to ecotopes as 'habitats'.

The Framework Criteria describes six core biophysical characteristics that have been agreed by the Aquatic Ecosystems Task Group as appropriate for the identification of High Conservation Aquatic Ecosystems or HCVAEs (and includes values such as Diversity, Distinctiveness, Vital habitat, Evolutionary history, Naturalness & Representativeness). In the NAWFA1 project each criterion was quantified ('scored') mathematically or statistically using multiple combinations of attributes calculated from the raw biodiversity surrogate data sets. At their meeting in October 2010, the AETG agreed to change the name of the HCVAE framework to the "High ecological Value Aquatic Ecosystem" (HEVAE) framework.

Aquatic ecosystem dependent species are those that depend on aquatic ecosystems for a significant portion or critical stage of their lives, or are dependent on inundation for maintenance or regeneration.

A planning unit in the NAWFA1 project is defined as the spatial unit at which the attributes and criteria for identifying HCVAEs were applied, and are hydrologically defined sub-catchments.

## 1.2 Risk assessment approach

The risk assessment process is now increasingly applied to catchments and their aquatic ecosystems because it is transparent, consistent and reliable (Diamond & Serveiss 2001, Serveiss 2002, Hart 2004, Hart et al. 2005). Needless to say, all steps in a risk assessment need to be guided at the outset by appropriate conceptual models (Burgman 2005), and this caveat applies to both qualitative and quantitative methods. Conceptual models are abstractions about how we think the world works in order to answer specific questions that may assist decision making, and usually takes the form of box and arrow diagrams. Drewery et al. (2006) suggested that conceptual models are basically process-based models hypothesising testable cause-effect relationships between stock-flow or storage-transport pathways. The overall approach, therefore, should be to first develop a conceptual model with stakeholders or end-users that captures the multiple threats and their pathways to multiple assets, and to then prioritise or rank them all based on a qualitative and/or semi-quantitative risk analysis. The most important step in ranking multiple risks occurs between the conceptual model and qualitative assessments where lesser or even trivial risks are filtered out in order to focus quantitative effort on more significant risks.

However, given the comprehensiveness of previous assessments undertaken in northern Australia (Table 1), the risk assessment process adopted here starts at the data analysis phase. All risk assessments in this section are underpinned by the “River Disturbance Model” of Stein et al. (2002; see section 2.3.1 & Fig. 5 below), which is essentially a “process-based” conceptual model of development threats to aquatic ecosystem assets. The quantitative ecological risk assessment (QERA) methodology adopted here is basically also an enhanced version of the spatially explicit semi-quantitative/qualitative Relative Risk Model (RRM) used in the TRIAP project (Bartolo et al. 2012), and reported in this Chapter 4. The critical interactions with stakeholders and end-users during this risk assessment process should be facilitated with the jurisdictional members on the NAWFA2 Project Steering Committee.

## 1.3 Revised Relative Risk model - project tasks

The main aim of Chapter 4 relates to Service requirement 4.2.3.

*Model and assess ecological assets identified for the Northern Australia Aquatic Ecological Assets Project and the likely impacts that these assets face as a result of development and climate change.*

The following project tasks/activities relate to this component.

- Activity 3: Update the spatially-explicit Relative Risk Model (RRM) used in the TRIAP project with spatial GIS data collated by Bartolo et al. (2008) and aquatic ecological assets data and predictive models reported in Kennard (2010, 2011).
- Activity 4: Incorporate climate change risk factors (*here specifically sea level rise in 2100*) in the RRM and in combination with the NAWFA1 predictive species distribution models developed by Kennard (2010); undertake an assessment to differentiate climate change risks from development risks; and examine potential interactions between them with respect to cumulative risks.
- Activity 6: Downscale existing climate maps/qualitative assessment.
- Activity 8: Highlight areas where development and predicted climate change will compound degradation.

A workshop was held in Darwin in April 2011 (Bayliss, Bartolo, Kennard & Close) to determine how the Relative Risk Model (RRM) developed as part of the TRIAP could be updated and improved for application to the current project. The RRM comprises the key assessment tool for climate change (sea level rise) and development risks to aquatic ecological assets across northern Australia, particularly HCVAE assets identified in the NAWFA1 project (Kennard. 2010). It was agreed at this workshop to update the TRIAP RRM with more recent ecological assets and threats data, to significantly enhance the methodology, and to undertake the RRM analyses at a finer spatial resolution (i.e. sub-catchments nested within river basins). The architecture of the RRM was therefore made more robust with respect to model and data uncertainties by incorporating more quantitative procedures (see modified RRM risk definition below), whilst at the same time still retaining its ability to rank and easily identify the most significant risk factors for further analysis. The RRM concept was therefore revised to:

- Assess and report risks at finer spatial scales in addition to basins/catchments. For example, by using the sub-catchment units (or planning units) developed by Kennard (2010) the spatial resolution was increased from 51 river basins (TRIAP) to 6,393 sub-catchments;
- Include spatially-explicit "surrogate" threat data based on River Disturbance Indices (Stein et a. 2002) updated to 2010 or there about;
- Include a sea level rise scenario (1m projection at 2100);
- At the focus catchment scale, include development scenarios from Chapter 4 of the Taskforce Science Review;
- At the focus catchment scale, examine the interaction between multiple stressors, on selected assets and, hence, potentially their cumulative effects.
- Using the predictive species distribution models developed in NAWFA1 by Kennard (2010), assess whether or not they can be intersected at a sub-catchment scale with both development and climate change (primarily sea level rise) risks to identify those aquatic system assets and species most at risk from these threats.

Activity 3 was hence modified to mean update and "revise" the RRM with more quantitative assessment methods that are amenable to uncertainty analysis and the incorporation of model outputs into Bayesian belief Networks (BBNs) for integration with other components of this project for future scenario simulations and transparent communication with end-users or stakeholders. To this end the task has been split into two: (i) update the RRM used in the TRIAP project incorporating updated land use and non-land use information (Bartolo); and (ii) revise the RRM to make it quantitative and incorporate the asset and threat layers generated by Kennard (2010) in the previous NAWFA Ecological project (here called NAWFA1).

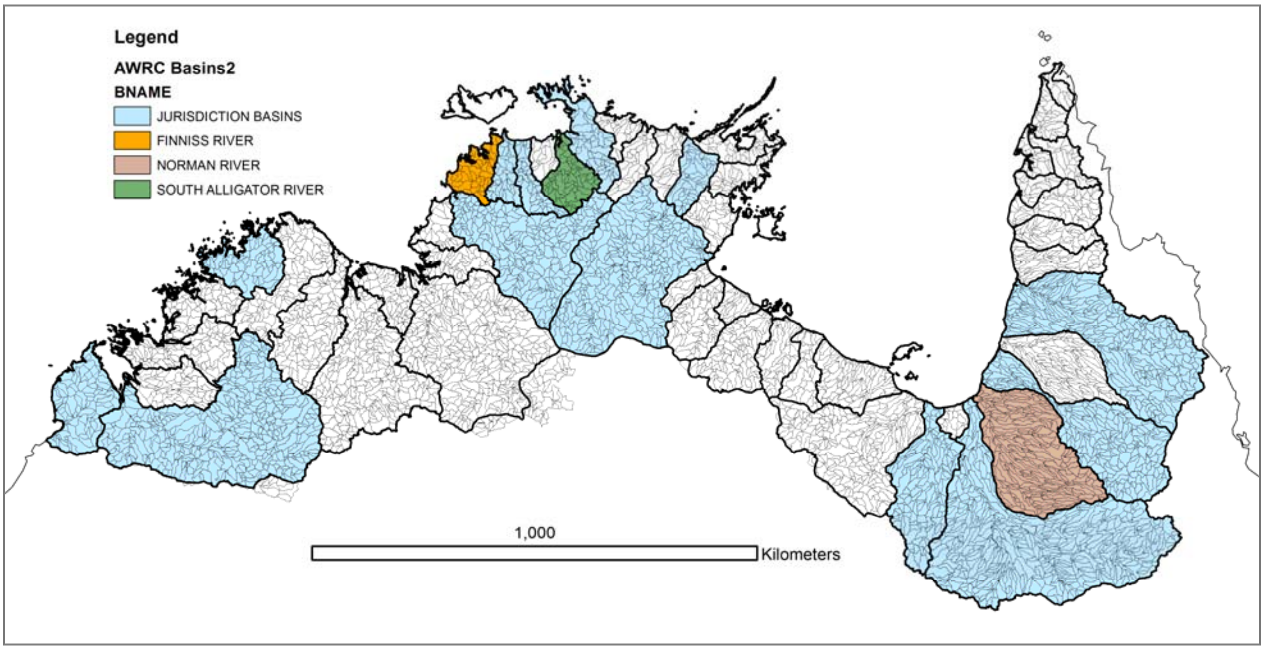
Additionally, Activity 4 has now been undertaken at the following two scales because of the possibility of scalar effects: (i) across northern Australia; and (ii) in the Finniss River, South Alligator River and Norman River study basins. An attempt will be made to differentiate the two effects operating at different time-scales and, therefore potentially, at different levels of interaction across the landscape. This approach provides an opportunity also to undertake a detailed comparison of both RRMs approaches (i.e. a comparison between semi-qualitative/quantitative & quantitative), as there will be advantages and disadvantages in using either method.

# 2. METHODS

## 2.1 Reporting units – AWRC basins & sub-catchment units

For compatibility with the previous TRIAP project, AWRC basins (Figure 1a) were chosen as the basic catchment-scale reporting unit (excluding islands). Basins flagged by the jurisdictions as special interest areas are blue, the Finniss River basin case study is orange and the South Alligator River and Norman River basins are green and brown, respectively (used in a later

(a)




(b)

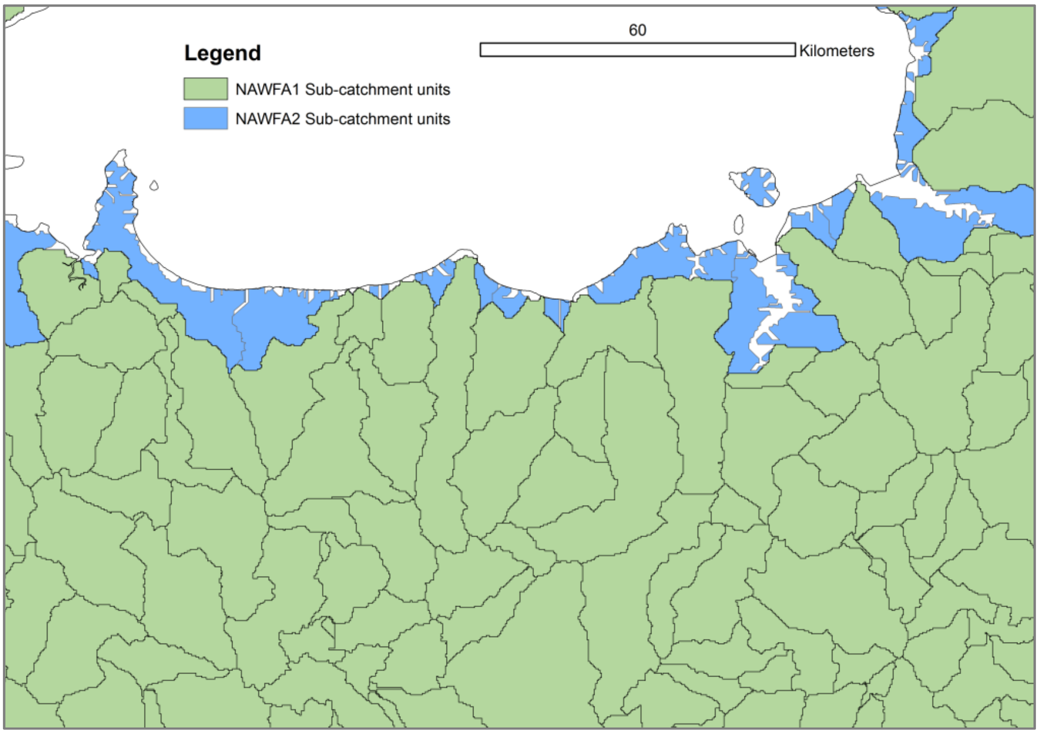



Figure 1a & b. (a) AWRC basins (black lines) and their sub-catchments units (grey lines). Basins flagged by the jurisdictions are blue, the Finniss River basin is orange, and the South Alligator River and Norman River basins are green and brown, respectively (see section 3.3). (b) Close up of the Southern Gulf of Carpentaria showing the sub-catchment units used in the NAWFA1 project (green, n=5,308; Kennard 2010) and the additional 1,085 coastal sub-catchment units used here (blue; new total=6,393).

comparison in section 3.3). The underlying unit of analysis in all risk assessments is the Planning unit or sub-catchment unit used in NAWFA1 (Fig. 1b). NAWFA1 was a study of freshwater aquatic assets (n=5,803 units) and, hence, did not include a very narrow coastal margin. However, NAWFA2 requires an assessment of sea level rise impacts and, hence, an additional 1,805 sub-catchment units were created (new n = 6,393).

## 2.2 Aquatic ecosystem assets

### 2.2.1 Aquatic ecosystems (AE)

The following three high level aquatic ecosystem types used in the NAWFA1project are used in all risk assessments as basic assets (see Kennard 2010, Auricht 2010; Table 2): Riverine, Palustrine and Lacustrine. Estuarine, Subterranean and Artificial systems are not included in the risk analysis.

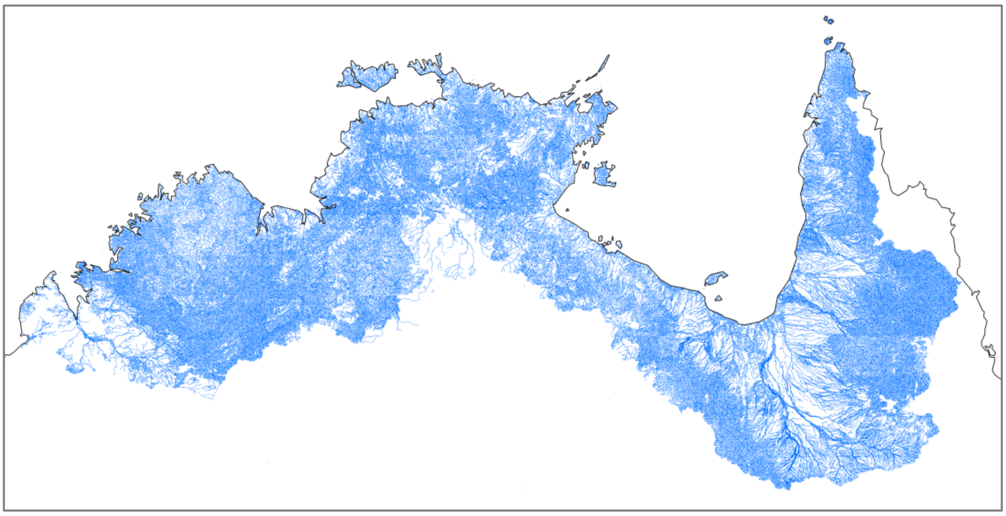
Table 2. Hydrosystems in northern Australia and their associated aquatic ecosystem types within the Australian National Aquatic Ecosystem (ANAE) classification scheme. From Kennard (2010), the classification scheme is after Auricht (2010).

| Hydrosystem | Ecotope types present in northern Australia |
|---|---|
| Estuarine | Semi-enclosed embayments receiving sea water and fresh water inputs, mangrove forests, saltmarshes, saltflats, intertidal flats. |
| Riverine | Rivers, streams and waterbodies that may have fringing aquatic vegetation (but not including the hyporheic zone). |
| Palustrine | Floodplains and vegetated wetlands such as marshes, bogs and swamps, including small, shallow, permanent or intermittent water bodies. |
| Lacustrine | Large waterbodies situated in a topographic depression or river channels that are largely open water features but may contain fringing aquatic and terrestrial vegetation. |
| Subterranean | Groundwater environments including the hyporheic zone and underground streams, lakes and water-filled voids. |
| Artificial | Reservoirs, farm dams, mine tailings dams, flood irrigated field, canals and drainage channels. |

The distribution of Riverine, Palustrine and Lacustrine freshwater aquatic ecosystems in the northern Australia study area are illustrated in Figures 2a & b respectively. Figures 3a shows the density of Riverine (total km stream) aquatic ecosystems per sub-catchment unit across northern Australia, and those for Palustrine and Lacustrine aquatic ecosystems (total $km^2$) in Figures 3b & c, respectively. Jenks natural breaks in the distribution of data are used to define at least three data classes in all distribution maps reported here (see Jenks & Caspall 1971).

A major assumption of the analysis reported here is that all estuarine habitats will be at very high risk of change with a 1m+ sea level rise by 2100 ( IPCC 2007), and that new estuarine habitats will likely be created as sea level rises. This analysis is more suited to the TRIAP RRM, which uses standard and easily recognised habitat types as units of asset assessment (e.g.

(a) Riverine



(b) Palustrine and Lacustrine

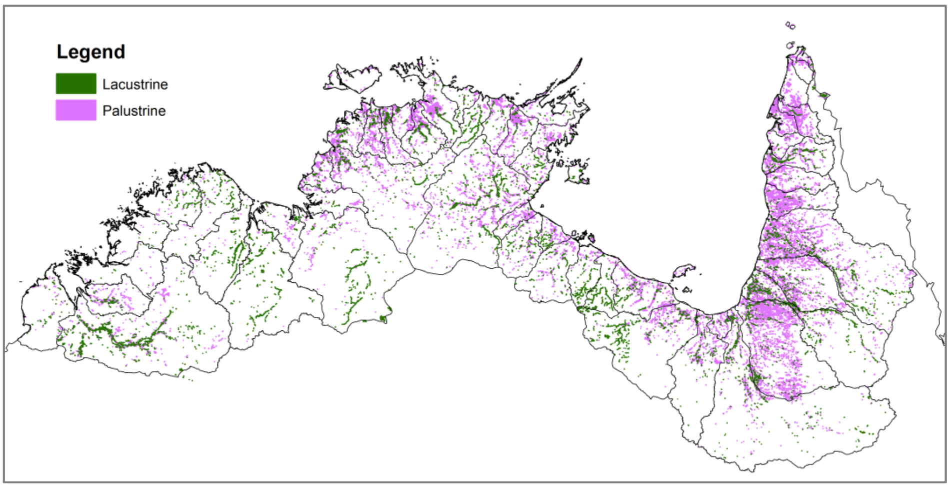



Figure 2a & b. Distribution patterns of (a) Riverine and (b) Palustrine and Lacustrine freshwater aquatic ecosystems in the northern Australia study area (AWRC basins shown).

Rivers & Streams; Wetlands, Floodplains & Lakes; Springs & Waterholes; Riparian; Mangroves (see section 2, Chapter 4). Figure 4a & b compares the two systems of classification of aquatic ecosystems in the Alligator Rivers Region of the Northern Territory.

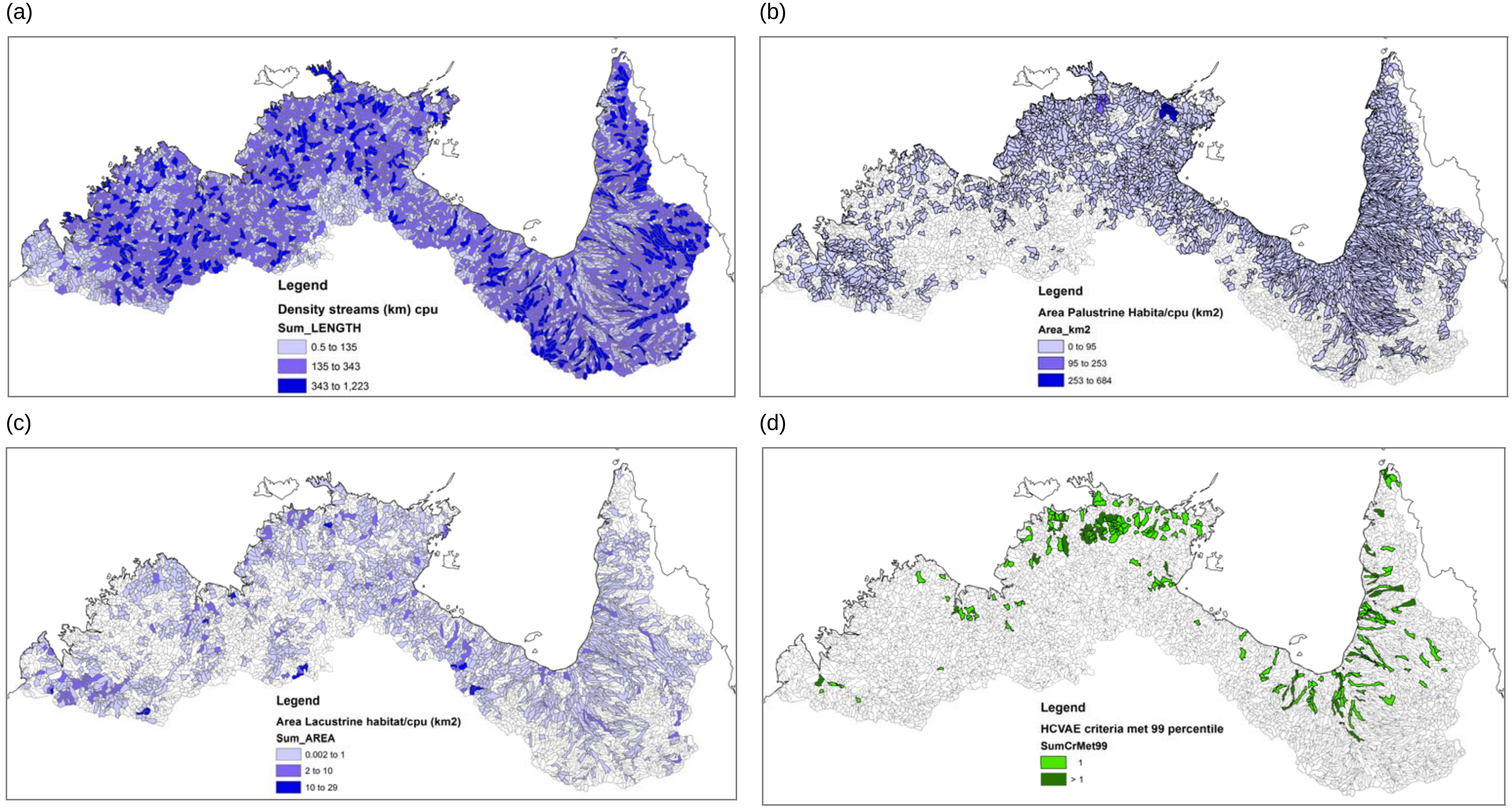
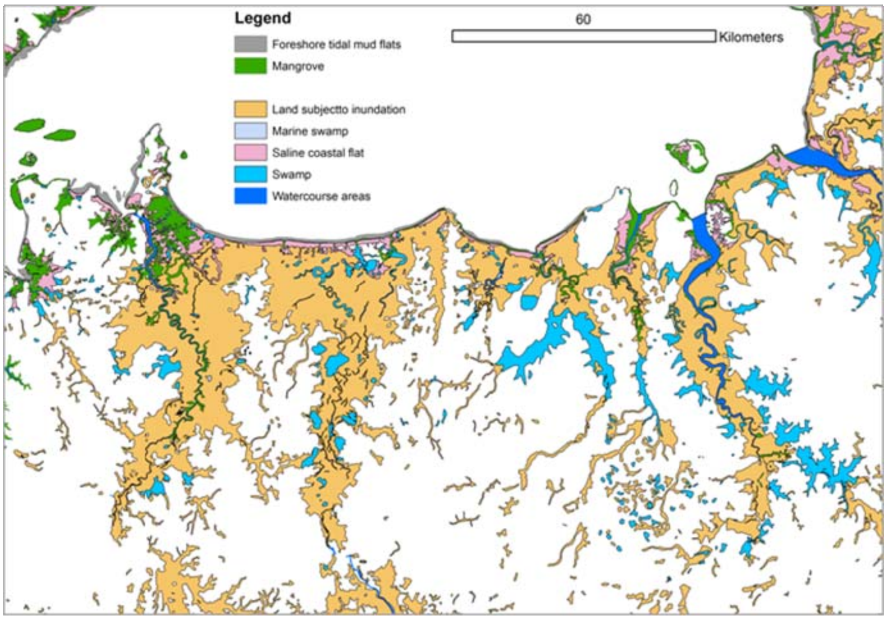



Figure 3a-d. (a) Density of Riverine (total km stream), (b) Palustrine (total $km^2$) and (c) Lacustrine (total $km^2$) aquatic ecosystems per sub-catchment unit across the northern Australia study area. (d) The distribution of HCVAE criteria met at the $99^{th}$ percentile (the sum of all Criteria); criteria 1 (light green) and > 1 (dark green, maximum of 4) are shown.

(a) Low-lying coastal habitats




(b) Aquatic ecosystem types

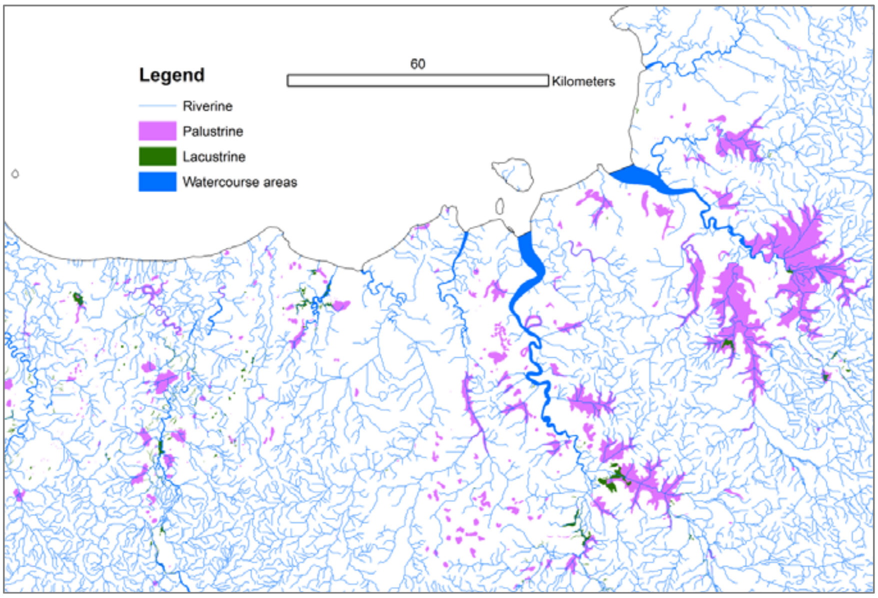



Figure 4a & b. (a) Low-lying coastal habitat layers (see map legend). (b) Close up of the Alligator Rivers Region (encompassing Kakadu National Park) showing the distribution of Riverine (blue), Lacustrine (green) and Palustrine (pink) freshwater aquatic ecosystems (after Kennard 2010).

### 2.2.2 High Conservation Value Aquatic Ecosystems (HCVAE)

The NAWFA1 project identified HCVAEs across the Northern Australia study area, and risk assessments were undertaken on these values in addition to the three freshwater aquatic ecosystem types. The criteria for identifying HCVAEs are as follows (from Kennard 2010):

1. Diversity: exhibits exceptional diversity of species or habitats, and/or hydrological and/or geomorphological features/processes.
2. Distinctiveness: is a rare/threatened or unusual aquatic ecosystem; and/or it supports rare/threatened species/communities; and/or it exhibits rare or unusual geomorphological features/ processes and/or environmental conditions.
3. Vital habitat: provides habitat for unusually large numbers of a particular species of interest; and/or it supports species of interest in critical life cycle stages or at times of stress; and/or it supports specific communities and species assemblages.
4. Evolutionary history: exhibits features or processes and/or supports species or communities which demonstrate the evolution of Australia's landscape or biota.
5. Naturalness: the aquatic ecosystem values are not adversely affected by modern human activity to a significant level.
6. Representativeness: contains an outstanding example of an aquatic ecosystem class, within a Drainage Division (but here applied across Northern Australia).

After a comprehensive and exhaustive quantitative assessment of the Framework used to identify HCVAEs, Kennard (2010) suggested that the most robust and transparent approach to identifying the subset of planning units (sub-catchment units) that are likely to contain aquatic ecosystems of the highest conservation value is simply to identify those that meet the threshold for one or more criteria (i.e. akin to the precautionary principle). They argued also that the total number of candidate planning or sub-catchment units can be restricted by simply using a strict threshold such as the $99^{th}$ percentile. Using this approach they hence identified a set of sub-catchment units potentially containing HCVAEs for each of three reporting scales: (i) the entire study region (275 sub-catchment units, 6.9% of total area); (ii) each drainage division (282, 6.9% of the total area); and (iii) each NASY region (308, 7.7% of the total area).

The approach adopted here was to assess Development and Sea Level Rise (SLR1) risks to sub-catchment units that met one or more Criteria at the $99^{th}$ percentile for the entire study region (see Fig. 3d). The composite metric is here re-scaled to a maximum value of 1.0 for use in subsequent risk assessment equations (see section 2.4.2).

### 2.2.3 Biodiversity surrogates

The NAWFA1 project examined the biodiversity values of the following four major aquatic ecosystem dependent taxonomic groups across northern Australia using species occurrence records at unique sampling locations: macro-invertebrates (343 locations); fish (3,866 locations, 103 species); turtles (374 locations, 13 species); and waterbirds (7,922 locations, 106 species). Due to data limitations (see Kennard 2010), macro-invertebrates are not included in subsequent analyses.

## 2.3 Threats to aquatic ecosystem assets

### 2.3.1 Risks from development

*Disturbance Indices*

The two components of the River Disturbance Index model developed by Stein et al. (2002), and used in the NAWFA1 project, are used here as high order surrogates of development threats in basins across the northern Australia study area (Fig. 5). These are the Catchment Disturbance Index (CDI) and the Flow Regime Disturbance Index (FRDI). Details of the model are show in Figure 5 and described by Stein et al. (2002). The Catchment Disturbance Index

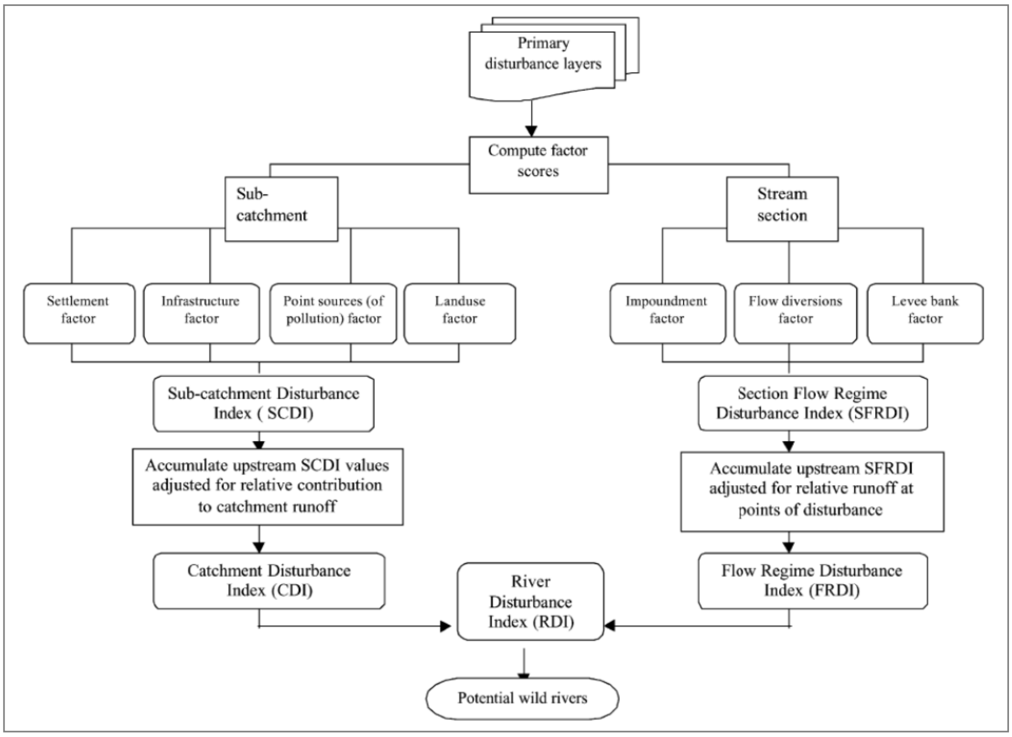



Figure 5. The River Disturbance Model of Stein et al. (2002) showing derivation of the catchment Disturbance Index (CDI), the Flow Regime Disturbance Index (FRDI) and their assessment endpoint, the River Disturbance Index (figure from Stein et al. 2002).

(CDI) is a catchment summary of human settlements, infrastructure, landuse and point sources of pollution that are expected to impact on aquatic ecosystem health (Stein et al., 2002). The method uses geographical data recording the extent and intensity of human activities known to impact upon river condition to quantify disturbance along a continuum from near-pristine to severely disturbed. The index is calculated as a runoff contribution-weighted summary of these impacts in the catchment upstream and within each planning unit. This index was calculated using the data on human activities detailed in Stein et al. (1998, 2002) with recent (2009) Land Use Mapping data for Australia (BRS 2009a), clearing information (BRS 2009b - Integrated Vegetation dataset) and infrastructure data from the Geodata TOPO 250K series 2 database (Geoscience Australia, 2003) The Flow Regime Disturbance Index (Stein et al., 2002) is a catchment summary of impoundments, flow diversions and levee banks within and upstream of each planning unit (calculated using data sources as per CDI). The model was applied to primary data sets across Australia and both indices are scaled to 1.0, hence making them ideal candidates for risk assessment as they represent risk probabilities for development threats. However, the maximum CDI value across the northern Australia study area is 0.7 and, hence, CDI values are re-scaled to 1.0. The maximum FRDI across Northern Australia is 1.0 and, hence, values were not re-scaled. To calculate the RDI assessment endpoint Stein et al. (2002) used the mean of the CDI and the FRDI values. However, this method is not used here for risk assessment (see section 2.4.2, combining two risks).

The distribution of Catchment Disturbance Index (CDI) per sub-catchment across the northern Australian study area is shown in Figure 6a and, that for the Flow Regime Disturbance Index (FRDI) in Figure 6b.

The re-scaled CDI and the FRDI are not physical entities as such, but amalgamated high order surrogates of diffuse spatial and non-spatial entities and disturbance processes. Hence, the development risk to aquatic ecosystems and HCVAE99 assets in sub-catchments were therefore assumed to be effectively captured by CDI and FRDI themselves, either separately or in combination.

### 2.3.2 Risk from climate change – sea level rise (SLR)

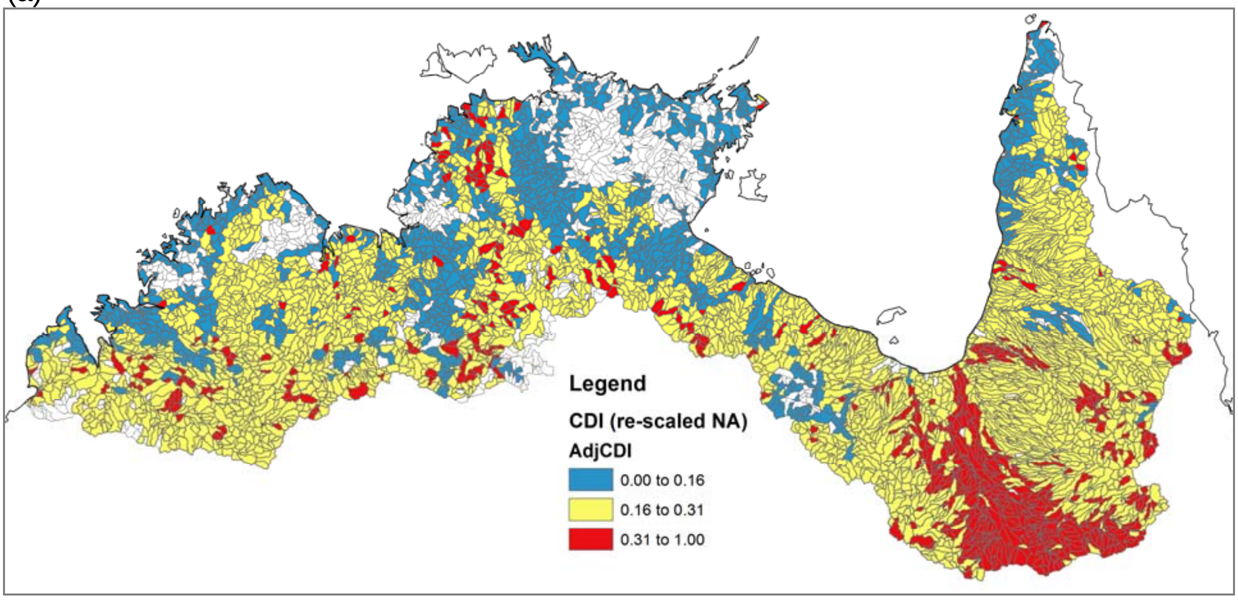
Coasts around the globe will be exposed to increasing risks from climate change and sea-level rise (IPCC 2007). Expected climate-related changes include: an accelerated rise in sea level of up to 0.6 m or more by 2100; a further rise in sea surface temperatures by up to 3°C; an intensification of tropical and extra-tropical cyclones; larger extreme waves and storm surges; and altered precipitation/run-off (Nichols et al. 2007). However, the mean rate of SLR has recently been revised towards the upper projection levels predicted by IPCC4 (see Church & White 2011). Freshwater aquatic ecosystems in coastal basins of northern Australia are vulnerable to SLR because they are low-lying, being generally situated within 0.2–1.2 m of Mean High Water Level (Hare 2003; Bartolo et al. 2012). In a recent study of SLR impacts on Kakadu's coastal wetlands, a 0.7m SLR projection was used based on advice from the DCCCE using a high emissions scenario and the latest climate change science (BMT WBM 2010: Kakadu-Vulnerability to climate change impacts). Hence, a mean SLR projection of 1m by 2100 is not unrealistic and would likely encompass the effects of increased storm surges coincident with peak tides. A 1m SLR was therefore chosen for risk analysis (& see Church et al. 2008, 2011).

A 1m sea level rise GIS layer was produced from the NASA Shuttle Radar Topology Mission (SRTM) 1 sec smoothed DEM, which was clipped to the project area and converted to a shape file between AHD (i.e. the zero datum for the Australian coastline) and an elevation of 1m. No corrections were made for potential storm surges or geomorphology and, hence, this process assumes a uniform sea level rise.

The extent of a projected 1m sea level rise (SLR1) in 2100 across the Northern Australia study area is shown in Figure 7a (for visualisation purposes the actual extent is exaggerated at this map scale with a 0.4mm thickness boundary). The proportion of each sub-catchment unit across Northern Australia that will be inundated by a projected 1m SLR is show in Figure 7b. Figures 7c & d are close-ups that show the intersection between aquatic ecosystem types and projected 1m (SLR1) and 2m (SLR2) sea level rises, for the Southern Gulf of Carpentaria and the Alligator Rivers Region, respectively.

The sea level rise risk for each aquatic ecosystem type in all affected sub-catchment units was estimated in a GIS by that proportion of the total area or km of steam that was intersected by the SLR1 layer. The SLR risk to HCVAE99 assets was estimated as the proportion of the affected sub-catchment area that was interested by the SLR1 layer.

(a)




(b)

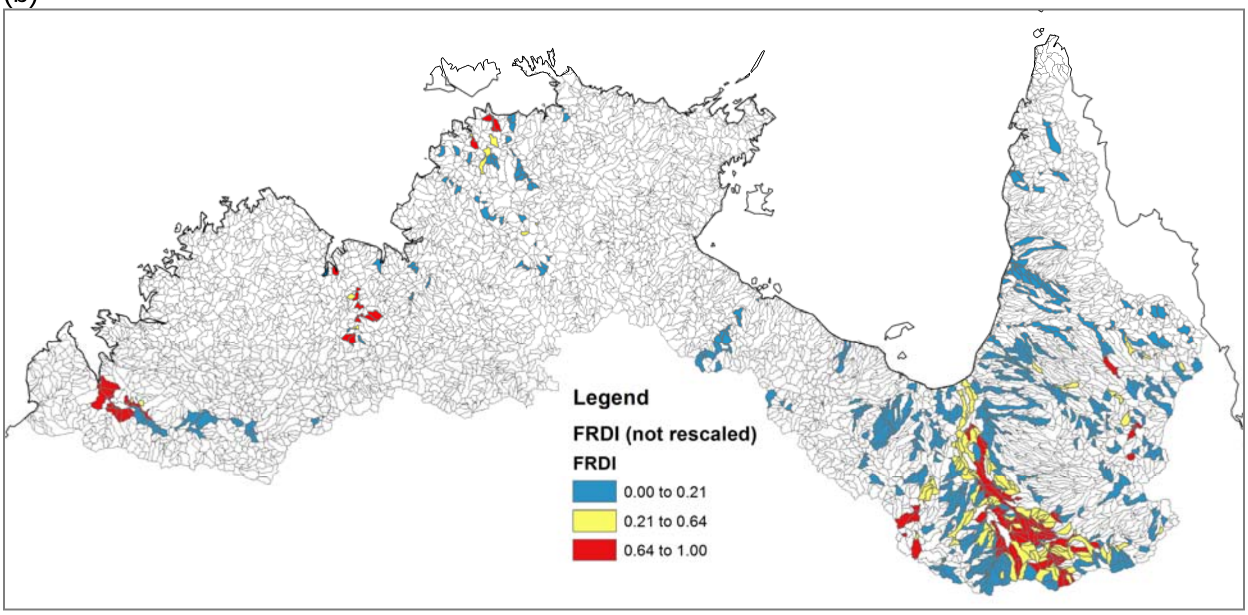



Figure 6a & b. (a) Catchment Disturbance Index (CDI) of sub-catchments across the northern Australian study area and, similarly, for the (b) Flow Regime Disturbance Index (FRDI). CDI values are re-scaled to the maximum value across Northern Australia.

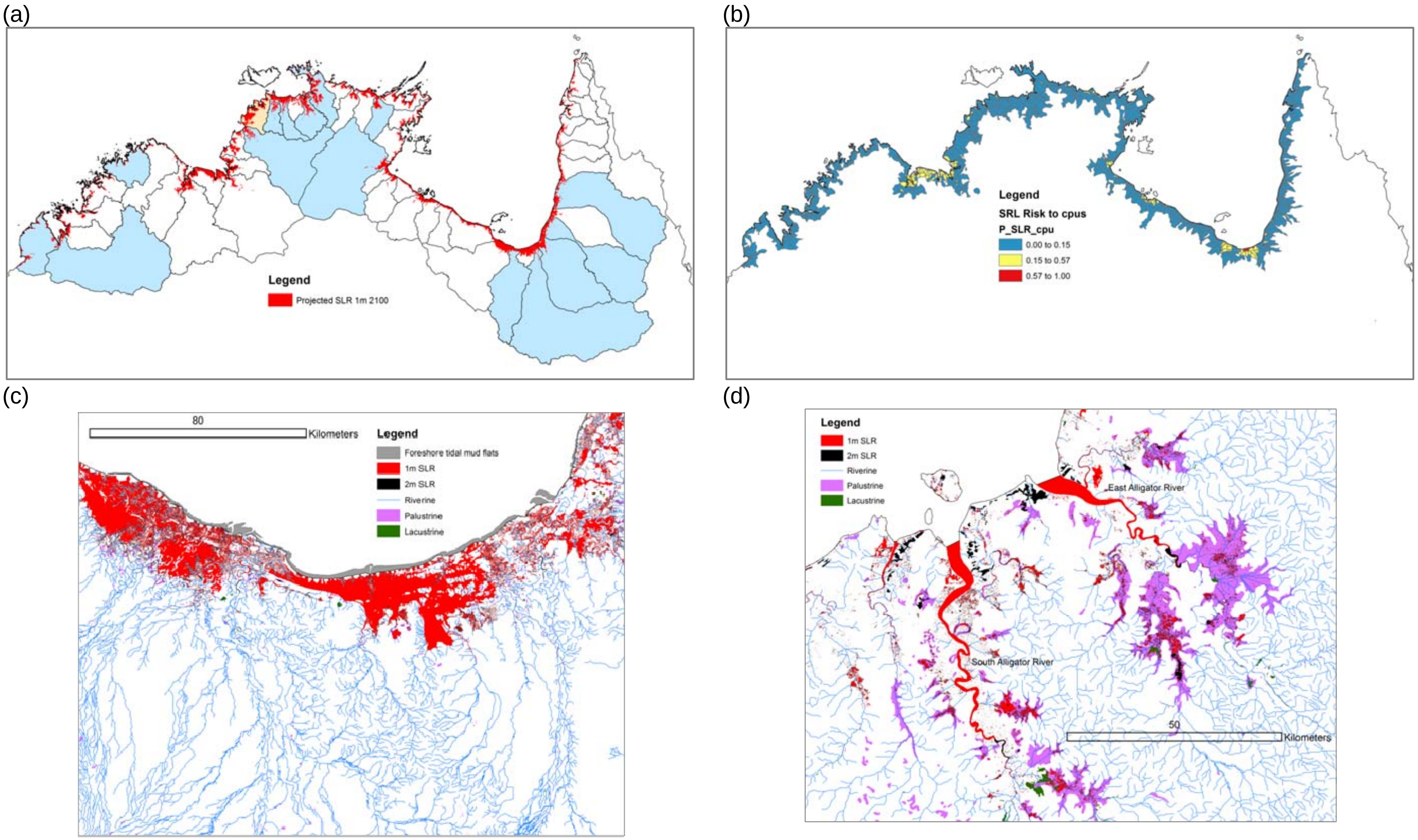



Figure 7a-d. (a) Coastal areas that may be affected by a projected 1m Sea Level Rise (SLR) across the northern Australia study area in 2100 (AWRC study basins in blue, Finniss R basin in orange). (b) SLR risks to sub-catchments (measure as the proportion of area inundated). (c) Aquatic ecosystems in the Southern Gulf of Carpentaria at risk from a SLR (red 1m rise; black a 2m rise but barely distinguishable). (d) Aquatic ecosystems in the Alligators Rivers Region (Kakadu National Park) at risk from a 1m and 2m SLR.

## 2.4 Quantitative Risk Assessment methodology

### 2.4.1 Reference frames

Clarity on what the spatial and temporal reference frames that are used in a risk assessment process is critical. Burgman (2005) defines risk as the probability of an adverse event over a given time frame. Hence, combining risks calculated over two different time frames (e.g. present day vs. future) is a dangerous exercise unless all assumptions and caveats are clearly stated.

*Temporal*

The most recent update to the primary data layers used in the RDI model (Stein et al. 2002) was made for the NAWFA1 project using data up to 2010 (Kennard 2010) and, hence, the reference time frame that Development risk apply to is for the year 2010. In contrast, sea level rise projections apply to 2100, almost a century in the future. However, in this report we examine the combined risks from Development and Sea Level Rise (SLR1) in an attempt to differentiate the effects of the two and where they may interact or exacerbate overall risk. Needless to say the underlying assumption is that after 89 years development would remain the same as in 2010, and this is of course nonsense. Regardless, it does provide a bottom line scenario from which developments can be projected at different time scales into the future (e.g. what if development in catchments doubles & therefore associated risks).

*Spatial*

Risks to aquatic ecosystem types and HCVAE99 values are reported at two spatial scales: (i) across the Northern Australian study area; and (ii) at the AWRC basin scale. The underlying spatial unit of analysis however, for both reporting scales, are the sub-catchments which are on average approximately 200 $km^2$ in size (Kennard 2010).

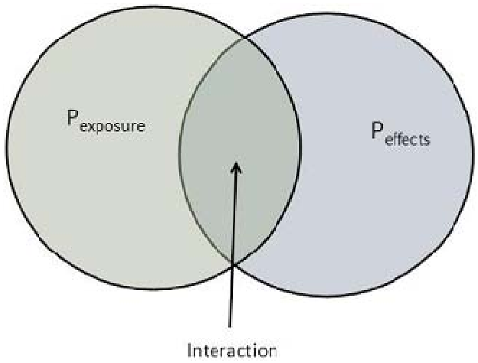
### 2.4.2 Calculation of risk probabilities

*Calculating risk from exposures & effects*

The probability of an adverse event is defined as the probability of exposure times the probability of effects, and is the interaction term derived by Bayesian statistics (see Venn diagram below & Bayliss et al. 2012).

$P_{risk} = P_{exposure} \times P_{effects}$

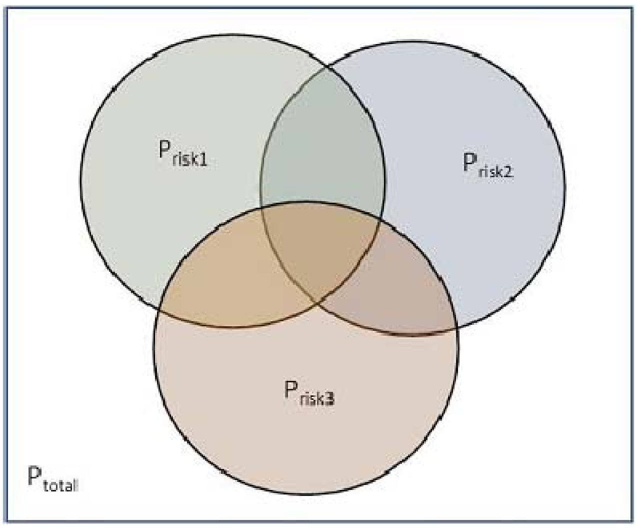
For example, a 1m sea level rise is predicted to occur by 2100 with 80% certainty (IPCC4 2007: Summary for Policy makers), hence, $P_{exposure} = 0.80$. If 50% of a freshwater wetland in a coastal sub-catchment is predicted to be inundated by saltwater as a result, then $P_{effects} = 0.50$. The risk to wetlands in that sub-catchment is therefore $P_{risk} = 0.45$, or the intersection or interaction between exposure and effects.




*Combining two or more risk probabilities*

Similar Bayesian logic is applied to the concept of combining two or more risks to the same asset, which is essentially re-scaling to a total risk probability of 10. For example, if the risk from Development (P1 in the Venn diagram below) to all aquatic ecosystems in a sub-catchment is 0.80 ($P_{DEV}$ = 0.80), and the risk of a 1m Sea level rise is 0.70 (P2 in the Venn diagram) to those same assets ($P_{SLR1}$ = 0.70), then the combined risk ($P_{COM}$) is:

$$P_{COMB} = P_{DEV} + P_{SLR1} - (P_{DEV} \ x \ P_{SLR1})$$




The interaction term is subtracted from the total to avoid double dipping (i.e. those assets affected by Development can't be affected by SLR & vice versa, although assumes that the effects are independent & not multiplicative).

For > 2 risk factors (P1, P2 & P3 in the Venn diagram) a short-hand formula is:

$$P_{COMB} = 1- \{[1-(P_1 \ x \ P_2)] \ x \ [1- (P_1 \ x \ P_3)] \ x \ [1-(P_2 \ x \ P_3)]\}$$

However, the underlying model assumption is additive because all risk factors are considered independent. That is, there are no multiplicative or compounding effects between them, and this may not be true.

### 2.4.3 Uncertainty analysis

*Characterisation of assets, threats and risks*

Despite the simple risk calculations above, observed exposure and effects data are intrinsically uncertain because they exhibit natural variability as would be reflected in the frequency distributions of their class size intervals (Bayliss et al. 2012). The probability distribution, or probability density function (pdf), of a random variable is the statistical term for a frequency distribution constructed from an infinitely large set of values where the class size is infinitesimally small (Palisade 2010). Hence, the frequency distribution of all risk variables used here over class size intervals is converted to continuous probability distributions that can be described by "Best Fit" equations chosen from a large range of candidate equations (Palisade 2010) and, which can be used to characterise the risk factor (essentially a "risk profile"). Individual and combined Development and SLR risks to aquatic ecosystems and HCVAE99 assets in sub-catchments across the northern Australia study area, or in selected basins, were therefore characterised using pdfs fitted to exposure and effects (where available) data. The pdfs were then used in conjunction with Monte Carlo simulation to account for uncertainty in the risk models. Monte Carlo methods are stochastic simulations that rely on repeated random sampling from a known distribution of data in order to estimate model parameters confidently, and are particularly useful for modelling systems with significant uncertainty in inputs such as the calculation of risk (Hilborn and Mangel 1997).

Risk modelling simulations were undertaken in an Excel™ - @Risk™ software environment (Palisade 2010). Where necessary combined risk variables were re-scaled to 1.0 using the Bayesian methods described above. The importance of parameter inputs to risk outputs was examined using sensitivity analysis of Monte Carlo outputs. All pdfs were randomly sampled 10,000 times or more to derive a stable mean value. There was little change in mean values when > 1 simulations were run (i.e. 2 to 100) and, hence, results reported here only apply to the first simulation of $10^3$ random samples. @Risk™ simulation results (Palisade 2010) include graphical displays of the distribution of all possible results from outputs (e.g. via relative frequency distributions & cumulative probability/distribution functions or cdfs), and generates sensitivity and scenario reports that help identify those inputs that are most critical to outputs. Sensitivity analysis is undertaken using regression analysis, whereby sampled input variable values are regressed against output values, leading to a measurement of sensitivity by input variable. Results of the sensitivity analysis are displayed as a 'Tornado' type chart, with longer bars at the top representing the most significant input variables in a positive or negative direction (Palisade 2010).

Probability distribution functions can be used to characterise the innate variability of any value, such as aquatic ecosystem assets (see Kennard et al. 2010b) and threats to those assets. All statistical functions used in subsequent risk analyses at all reporting scales are summarised in Appendix A (Table 6a-e, & see below).

## 2.5 Reporting scales

### 2.5.1 Northern Australia NAWFA region

*Across basins*

A total of 53 AWRC basins in the NAWFA2 study area are reported here (Table 3, Fig. 1a), and exclude basins from the east coast of Australia, Torres Strait and large islands such as Melville and Bathurst Islands and Groote Eylandt.

Table 3. AWRC Basins used in this study. Basins selected by jurisdictions for attention are highlighted in blue, and the Finniss River case study basin highlighted in orange.

| Basin | |
|---|---|
| **Adelaide River** | Limmen Bight River |
| Archer River | Liverpool River |
| Blyth River | **Mary River** |
| Buckingham River | McArthur River |
| Calvert River | **Mitchell River** |
| **Cape Leveque Coast** | Morning Inlet |
| Coleman River | Moyle River |
| **Daly River** | Nicholson River |
| Drysdale River | **Norman River** |
| Ducie River | Ord River |
| **East Alligator River** | Pentecost River |
| Embley River | Prince Regent River |
| **Finniss River** | Robinson River |
| Fitzmaurice River | **Roper River** |
| **Fitzroy River** | Rosie River |
| **Flinders River** | Sandy Desert |
| **Gilbert River** | Settlement Creek |
| Goomadeer River | **South Alligator River** |
| **Goyder River** | Staaten River |
| Holroyd River | Towns River |
| Isdell River | Victoria River |
| Jardine River | Walker River |
| Keep River | Watson River |
| **King Edward River** | Wenlock River |
| Koolatong River | Wildman River |
| **Leichhardt River** | Wiso |
| Lennard River | |

*Basin means*

The inherent variability of assets and risks between sub-catchment units across northern Australia was large as the statistical distribution functions indicate (Appendix A, Table 6b & see below). Hence, basin means are also used to analyse risk in an attempt to reduce this variability. We therefore treat variability in risks between basin means as a key attribute at this reporting scale. Key mean variables by basin that were used in risk assessments are summarised in Appendix B (Table 6).

### 2.5.2 Basins flagged by jurisdictions

The basins flagged by the jurisdictions for special attention are highlighted at all reporting scales. Three basins were selected for more detailed analysis and comparison (see below).

### 2.5.3 Comparing basins with different risk factors

*The South Alligator River & Norman River basins*

The South Alligator River and Norman River basins were chosen for more detailed comparison of risk because of their contrasting land uses, reflecting a high value conservation area (Kakadu National Park) and intensive land use and associated catchment disturbance, respectively (see Fig. 1a, green & brown highlighted basins). All statistical functions used in subsequent risk analyses are summarised in Appendix A (Table 6c, & see below).

### 2.5.4 Finniss River case study – comparing methodologies

The Finniss River basin in the Northern Territory was chosen as a case study area to compare RRM methodologies at a fine scale resolution. Additionally, Bartolo et al. (2012) identified this basin as being most at risk from development pressures due to an expanding urban population in nearby Darwin (see Fig. 1a & 7a, basin highlighted in orange). Hence, future development scenarios may be assessed with a greater degree of certainty than for other basins in the study area. All statistical functions used in risk analyses are summarised in Appendix A (Table 6d, & see below).

Whilst both RRM approaches are spatially explicit and address the same Development and SLR threats, their assessment pathways and endpoints are sufficiently different to make any meaningful comparison difficult except at a high level. They are essentially “apples” and “oranges” in the risk assessment tool box that fulfil different functions in order to achieve the same goal. Each methodology has their own strengths and weaknesses (e.g. see Table 5.1 in section 1). Hence, overall risk results using both methodologies are first compared at the basin level across the NAWFA study area using 14 selected by jurisdictions for special attention, and the Finniss River basin. A comparison is then made at a finer sub-catchment level of resolution in the Finniss River basin.

## 2.6 Climate change risk to biodiversity

### 2.6.1 Risk from sea level rise (SLR)

A Habitat Suitability Models (HSM) was developed for each species in the NAWFA1 project based on relationships between species’ occurrences and environmental attributes (Kennard 2010). The risk from Development and Sea level rise (SLR) was assessed for selected species in each sub-catchment by examining the intersection with both threats where they are predicted to occur. Species were selected arbitrarily for demonstration purpose only, however an attempt was made to include species with restricted and broader ranges within each fauna group.

*Turtles*

Species selected are: the Long-neck turtle; the pig-nose turtle; the Gulf-snapping turtle; and the Red-faced turtle.

*Freshwater fish*

Species selected are: the Barramundi; the Common archer fish; the Golden goby; and the Sooty grunter.

*Waterbirds*

Species selected are: the Magpie goose; the Green pygmy goose; the Great cormorant; and the Glossy ibis.

### 2.6.2 Risk from changes in rainfall & ambient temperature

There are few quantitative predictions for the impacts of climate change on the biodiversity of freshwater fauna in Australia, with implications for the future conservation and restoration of freshwater aquatic ecosystems (Davies 2010). One exception is the species distribution models developed by Bond et al. (2011) for 43 species of freshwater fish from Victorian streams based on a suite of hydro-climatic and catchment predictors, which were used to explore predicted range shifts under future climate-change scenarios.

However, given time constraints, no attempt was made to quantify risks to aquatic biodiversity across the study area as a result of changes in other climate-related variables such as rainfall and temperature. This is examined in detail for a handful of species in selected basins in Chapter 3, where hydrological and ecological thresholds in relation to the 2030 development and climate change scenarios used in the NASY project. Nevertheless, the NAWFA1 data sets are comprehensive and, used in combination with the OzClim climate scenario simulation tool (CSIRO 2008), may offer future opportunities for quantitative risk assessments out to 2100 (rather than 2030), and this is briefly explored in this section.

Selected species from the huge array of predicted species distribution maps developed in the NAWFA1 project by Kennard (2010) were overlaid with the spatial extent of the following two OzClim (Ricketts & Page 2007, CSIRO 2008) climate change scenarios for 2100 in an attempt to develop a method to characterise potential exposures over large geographic regions:

1. A hotter climate (via temperature change $^{0}$C/y).
2. A hotter and wetter climate (via rainfall change mm/y).
3. A hotter and drier climate (via rainfall change mm/y).

## 2.7 Integrating Bayesian Belief Network (BBN)

A BBN is a probabilistic model of a system and its conditional dependences, as represented by a directed acyclic graph consisting of variable nodes and links (Marcot et al. 2001, 2006; Bayliss et al. 2012, Chan et al. 2010a & b, Batchelor & Cain 1999). The structure of a BBN is based on a conceptual model where causal relationships are made explicit and the probabilistic relationships between variables can be updated using Bayes' Theorem (Hart 2004). Node values are determined by mutually exclusive discrete states (McCann et al. 2006), for example such as

High and Low risk. Each 'parent' node takes as input a particular set of values from 'child' nodes to give the probability of the variable state that they represent (Bayliss et al. 2012). The conditional relationships, or dependencies, between parent and child nodes are defined by Conditional Probability Tables (CPT) that underlies each node.

The risk outputs reported here were incorporated into a BBN using Netica$^{TM}$ software (Netica 2010; see Cain 2001). The structure of the BBN mirrors the conceptual risk model used in all analyses to assess the individual and combined threats from Development and SLR to aquatic ecosystems and HCVAE99 assets. Additionally, the Development component of our risk model is itself underpinned by the conceptual River Disturbance Model developed by Stein et al. (2002). Whilst BBNs are not amenable to advanced modelling techniques, they are a much more powerful communication tool than most risk software because they are graphically based and so more suitable as a decision making tool for stakeholders . The cascade effect of a change in variable state, or the subjective value of a decision, and/or the uncertainty associated with it, can be observed instantaneously.

Variable nodes in the BBN that represent different state levels of aquatic assets, threats or risks were all underpinned by either a probability density function (pdf) that characterises the frequency distribution of their mean basin value across the study area, or by equations. The formulae outlined above (section 2.4.2) used to combine exposure probabilities, or to combine two or more risk probabilities, were used as equations in the BBN with continuous data outputs converted to discrete data. The statistical functions used in the BBN were first assessed by @Risk (Palisade 2010, v5.7) software using their "Best Fit" procedure (Appendix A, Table 6a-e). However, compared to @Risk, there is a limited selection of "off the shelf" pdfs available in Netica$^{TM}$ and, hence, an alternative computational method was derived for incorporation into the BBN (see Results section 3.6).

To choose the appropriate level of a parent or child node in the BBN, users (e.g. basin managers) are referred to the summary tables of mean basin asset and threat data in Appendix B (Table 6).

# 3. RESULTS

## 3.1 Northern Australia NAWFA region

### 3.1.1 Risk assessment across basins

*Spatial distribution of risks*

The extent and intensity of Development risks (2010) to Riverine, Palustrine and Lacustrine aquatic ecosystems across the northern Australia study area are illustrated in Figures 8a-c, respectively. Similarly, the Development risks combined across all aquatic ecosystem types are illustrated in Figure 8d. The highest Development risks are concentrated around three broad regions with predominantly agricultural land use: the Ord-Pentecost basins (WA); the Finniss-Adelaide-Mary-Roper basins (centred on Darwin, NT); and basins in the southern Gulf of Carpentaria (GoC)-western Cape York (Qld). Of the three regions the southern GoC basins show the greatest risk from development.

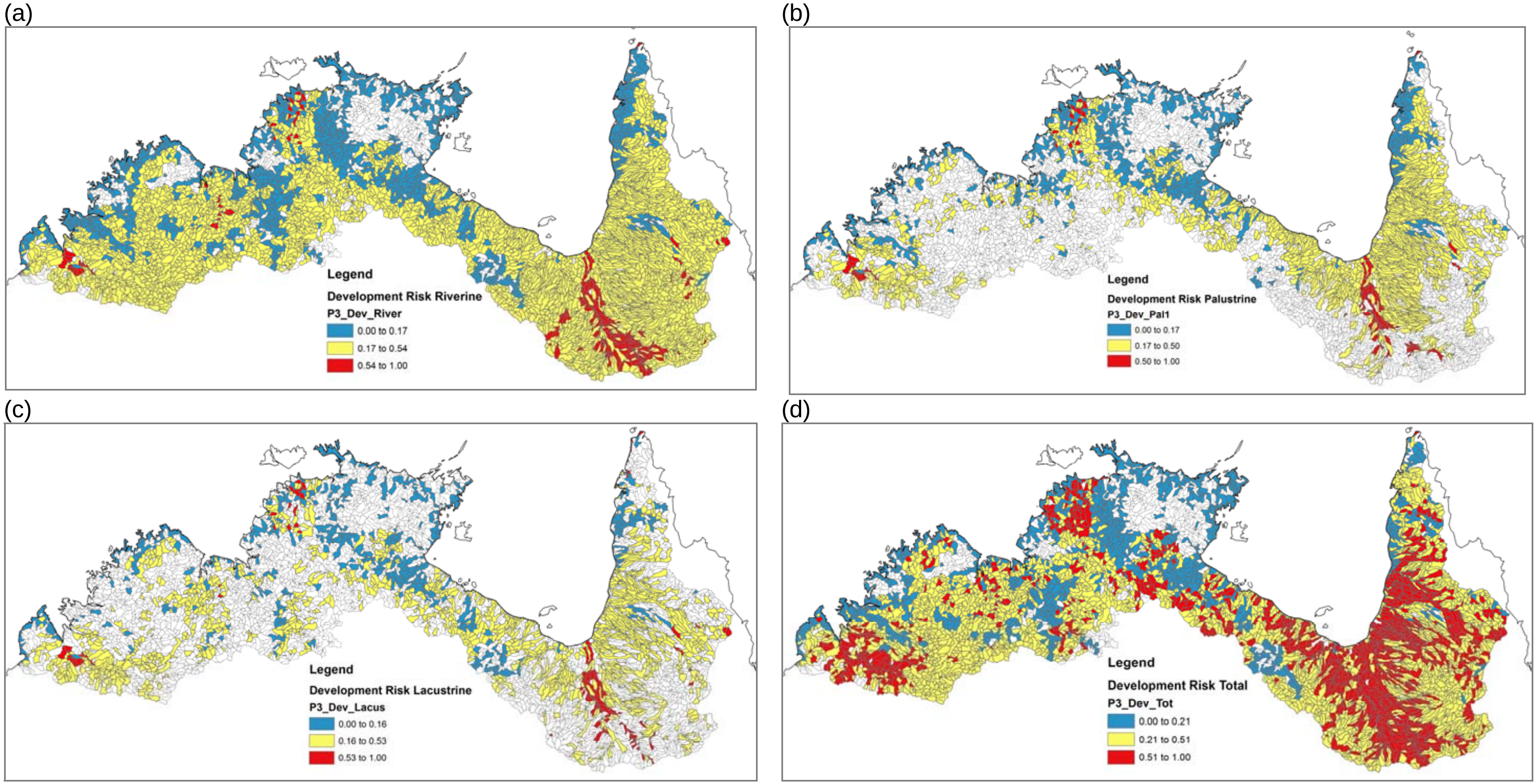



Figure 8a-d. Development risks in 2010 to: (a) Riverine; (b) Palustrine; and (c) Lacustrine aquatic ecosystems. (d) Total development risks combined across aquatic ecosystem types.

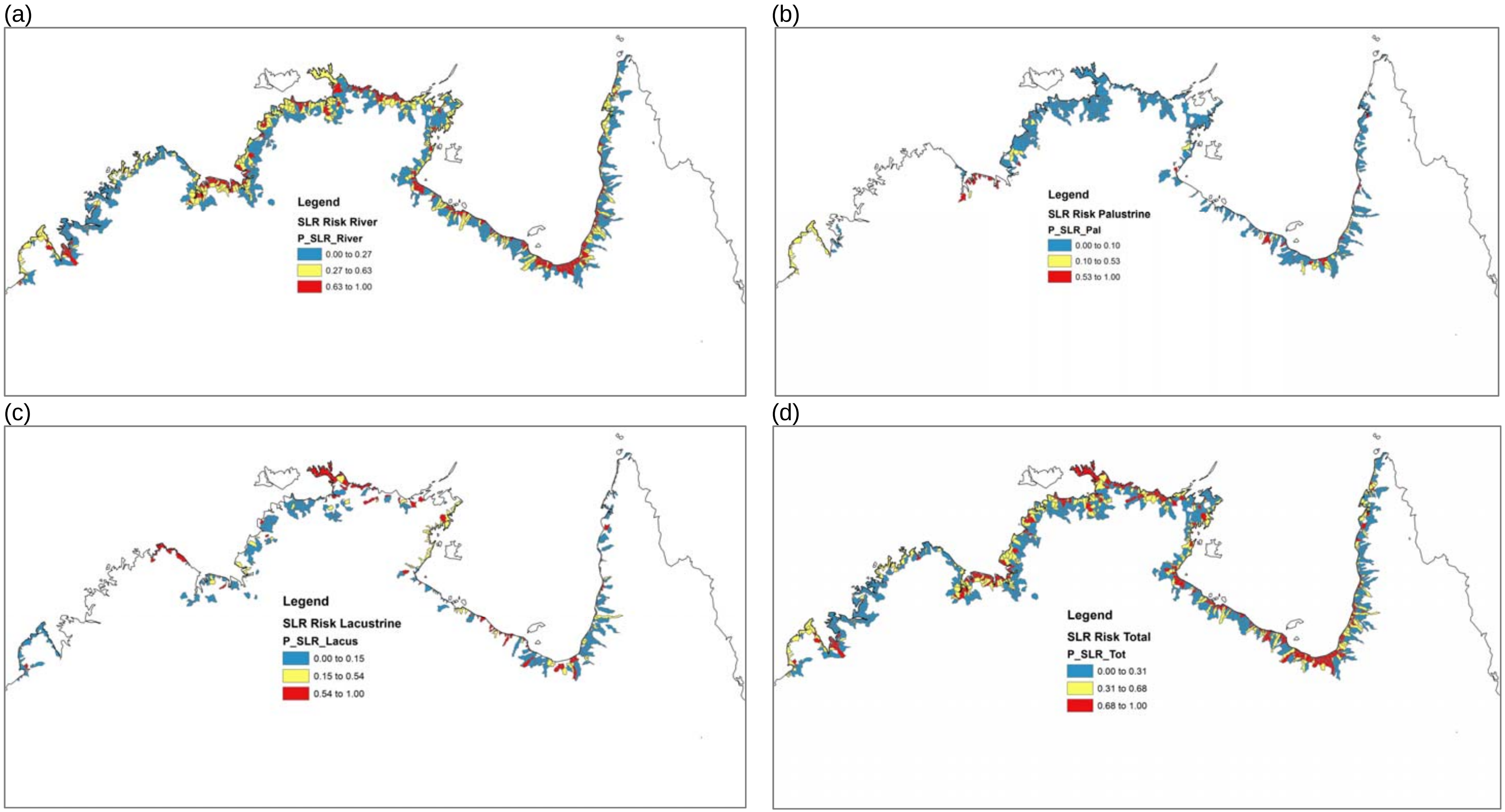



Figure 9a-d. Sea level rise risks (SLR) to: (a) Riverine; (b) Palustrine; and (c) Lacustrine aquatic ecosystems in 2100 across the northern Australia study area. (d) SLR risks combined across all aquatic ecosystems.

The extent and intensity of a 1m SLR risk to aquatic ecosystem types across the study area are illustrated in Figures 9a-c, respectively. Similarly, the total SLR risk combined across all aquatic ecosystem types is illustrated in Figure 9d. Although the distribution of SLR risks across the northern coastline is patchy, three regions stand out: Joseph-Bonaparte Gulf (WA); northern Arnhem Land (NT); and the southern GoC (Qld).

The extent and intensity of the combined risk from Development and SLR risk is illustrated in Figure 10, and assumes that risks from development will remain constant for the next 88 years. The following four broad regions of high combined risk were identified: the Ord-Pentecost basins (WA); the Finniss-Adelaide-Mary-Roper basins (all around Darwin, NT); Joseph-Bonaparte Gulf; basins in northern Arnhem Land (NT); and basins in the southern GoC-western Cape York (Qld) region. These spatial results indicate also that some regions without significant current development will still be at high risk but from SLR (e.g. Joseph-Bonaparte Gulf & northern Arnhem Land).

The extent and intensity of risks to HCVAE99 values from Development in 2010 and a 1m SLR in 2100 are illustrated in Figures 11a & b, respectively, showing much regional variation. Development risks to HCVAE99 assets were greatest in basins around Darwin and the upper Daly River basin (NT), and in southern GoC and western Cape York basins (Qld). Sea level rise risks to HCVAE99 assets were greatest in the Adelaide-Mary basins, basins of in Alligator Rivers Region (NT) encompassing Kakadu National Park, the coastal sub-catchments of the Roper River basin, and coastal sub-catchments of basins in the southern GoC and western Cape York.

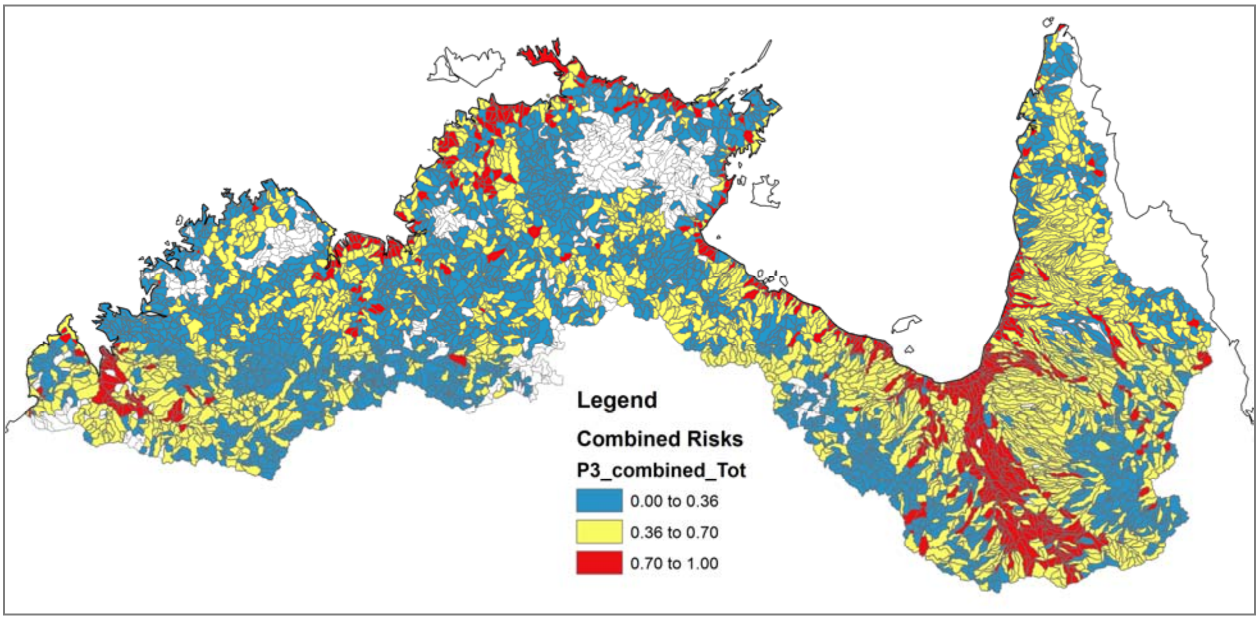
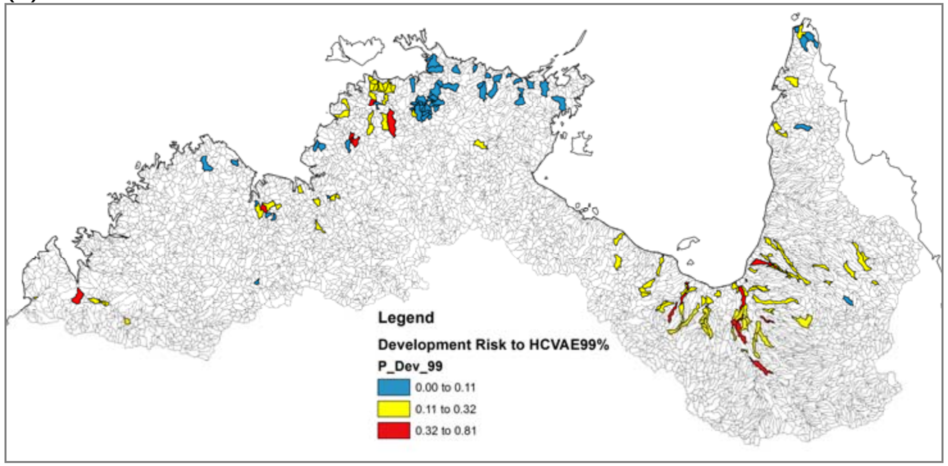
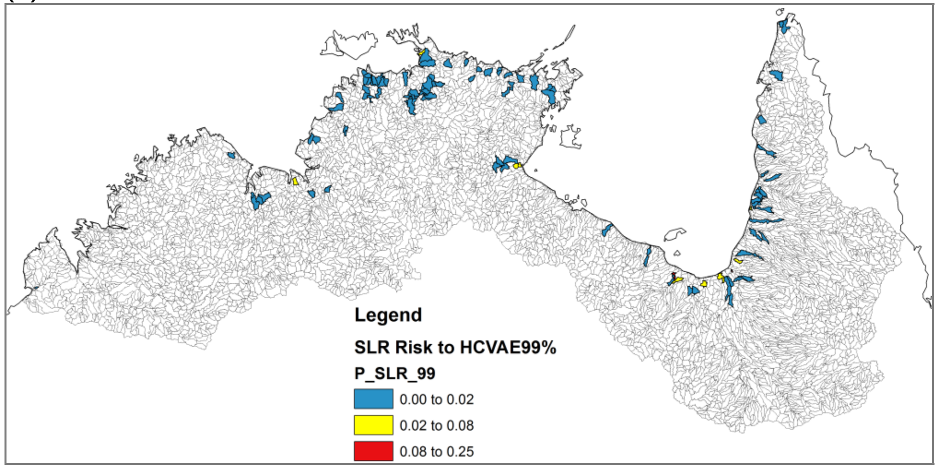



Figure 10. The combined total risks to aquatic ecosystems from Development and a 1m Sea Level Rise (SLR) in 2100 (& assumes that Development risks will remain constant after 89 years).

(a)




(b)




(c)

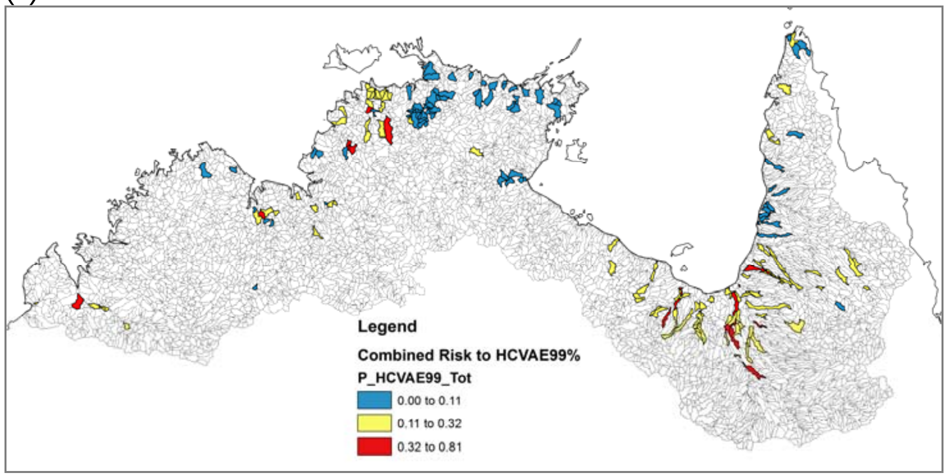



Figure 11a-c. Risks to HCVAE99 assets (sum of criteria met at the 99$^{th}$ percentile) from: (a) Development in 2010; and (b) a 1m sea level rise (SLR) in 2100. (c) Combined total risks in 2100 (& assumes Development risk will remain constant after 89 years).

*Asset & threat characterisation*

The occurrences of aquatic ecosystem types across the northern Australia study area were first characterised using "Best Fit" statistical functions (Palisade 2010) applied to the frequency of sub-catchment density data (n=6,393 or < if the ecosystem type did not occur in a sub-catchment). All statistical functions used to characterise aquatic ecosystem, and HCVAE99 assets, are summarised in Appendix A (Table 6a). By way of example, the relative frequency distribution and cumulative probability function for Riverine ecosystems are illustrated in Figure 12a&b, respectively. On average there is 134 km of Riverine ecosystem per sub-catchment and 2.8 and 0.2 $km^2$ of Palustrine and Lacustrine ecosystems, respectively. There is about 12 times more Palustrine than Lacustrine ecosystem in the study area.

(a) (b)

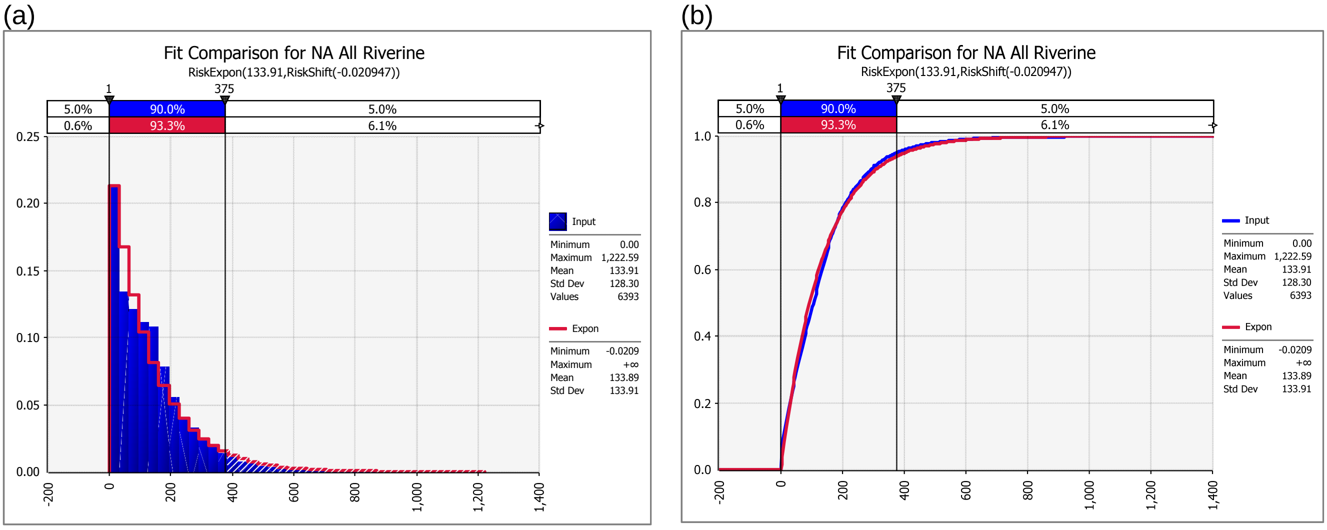



Figure 12a & b. Characterisation of Riverine ecosystems using "Best Fit" statistical functions applied to sub-catchment data (see text). (a) Relative frequency and (b) cumulative probability distributions (observed data blue, predicted data red). Similar functions were derived for Palustrine and Lacustrine ecosystems, and HCVAE99 assets (sum of all criteria met at the 99$^{th}$ percentile, after Kennard 2010), see Appendix A (Table 5a).

Threats from Development in 2010 and SLR in 2100 to aquatic ecosystems and HCVAE99 assets were also characterised using "Best Fit" statistical functions (Palisade 2010) using sub-catchment CDI and FRDI data. On average the re-scaled CDI is 6 times greater than the FRDI (0.19 cf. 0.03), and this difference is maintained using raw CDI data.

The threat to aquatic ecosystems within sub-catchments from a 1m SLR was estimated directly by the area of overlap (intersection) with a projected 1m SLR. The overlap areas ($km^2$) were converted to proportions and comprise an estimate of SLR risk to those ecosystem types. The threat from a 1m SLR to sub-catchments identified as having HCVAE99 assets was simply estimated by the proportion of the sub-catchment inundated by sea water.

*Risk profiles*

Risk profiles for Development and SLR threats to aquatic ecosystem were then derived using the risk calculation methods outlined in section 2.4.2 and the statistical methods used to characterise assets and threats data described above. Monte Carlo simulations (n=10,000) were undertaken to capture innate variability in data distributions and to derive stable mean values

(Palisade 2010). Statistical functions of risk profiles that exhibited minimum and maximum values outside of the 0 to 1.0 boundary condition for a probability value were truncated for simulation purposes, resulting in slight biases of mean values (< + 4% for Development risks & < +1 % for SLR risks).

Risk profiles for Development and SLR threats to each aquatic ecosystem type, and to HCVAE99 assets, are summarised in Appendix A (Table 6a). The contrast in Development and SLR risk profiles to all aquatic ecosystem types combined is illustrated in Figure 13a & b. Results show that Development risk in 2010 is about 5 times greater than a projected SLR risk in 2100 (0.39 cf. 0.08, respectively). However, SLR risks will likely exacerbate current development risks. The profiles show also that Development risks have higher values across a broader range that did SLR risks. In contrast, Development risks in 2010 to HCVAE99 assets were about 23 times that of SLR rise risk in 2100 (0.0045 cf. 0.0002), however, with the overall combined risk being very small (< 0.005 or ~ 0.5%).

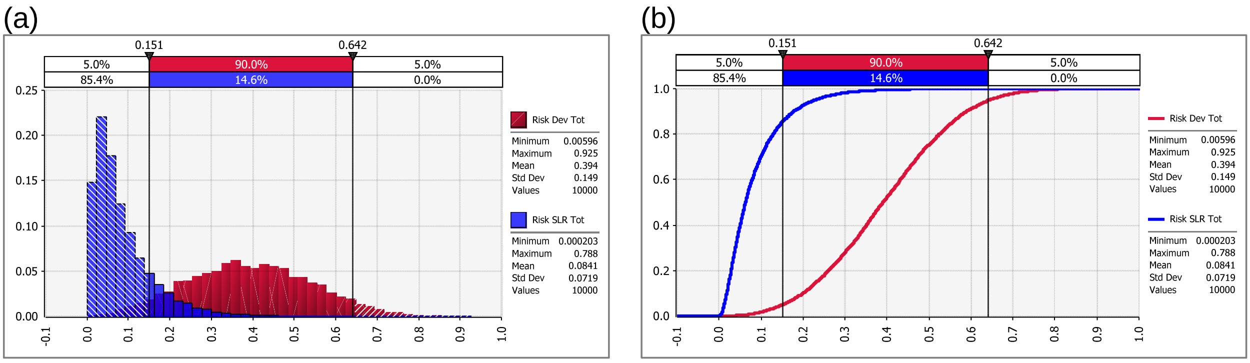



Figure 13a & b. Contrast in Development (red) and SLR (blue) risk profiles across northern Australia basins for aquatic ecosystem types combined. (a) Relative frequency distribution and (b) cumulative probability functions.

*Uncertainty analysis*

Monte Carlo simulations (n=10,000) and sensitivity analysis using @Risk software (Palisade 2010) were undertaken on all risk profiles to ascertain the relative contributions of each risk factor to total risk. Probability density functions (pdfs) are used in simulations rather than relative frequency distributions. Sensitivity analysis shows that Riverine ecosystems contributed most to total Development risk, followed closely by Palustrine ecosystems, with Lacustrine ecosystems contributing the least (Fig. 14a-c). Similar trends were found for total SRL risk, but with Riverine ecosystems contributing about 7 times more than Palustrine ecosystems (Figs. 14d-f). Sensitivity analysis showed also that Development risk contributed about 4 times more than SLR risk to the combined risk (Figs. 14g-i), but assumes that development will remain constant to 2100. The Development and SLR risks to HCVAE99 values were too small to warrant uncertainty analysis.

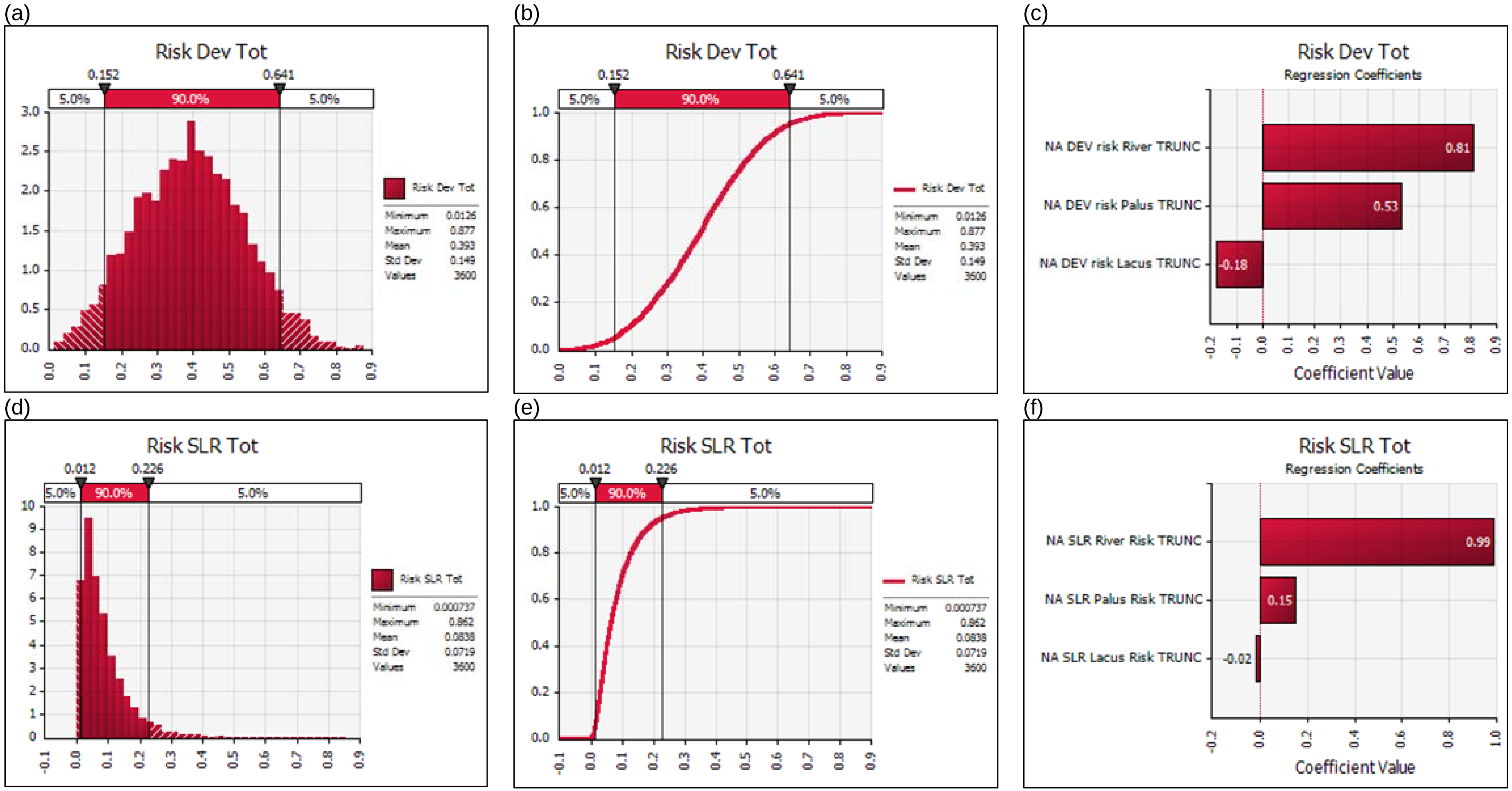



Figure 14a-i. Sensitivity analysis for: (a-c) total Development and (d-f) total Sea Level Rise (SLR) risks to Riverine, Palustrine and Lacustrine ecosystems. (a & d) Probability distribution functions (pdf), or total risk profile, for Development and SLR threats, respectively. (b & e) Cumulative probability functions for Development and SLR threats, respectively. (c & f) Tornado graphs showing the relative contributions of each aquatic ecosystem type to the total Development and SLR risk, respectively. (g-i) Similarly for the total Combined risks (Development & SLR) to aquatic ecosystems.

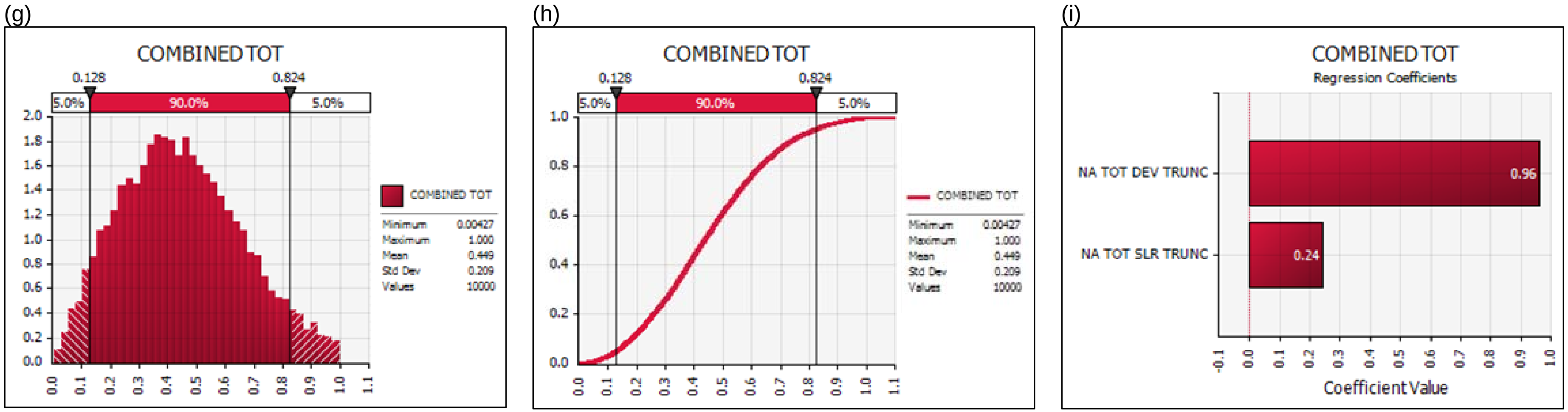

(g)
COMBINED TOT
0.128
0.824
5.0%
90.0%
5.0%
COMBINED TOT
Minimum 0.00427
Maximum 1.000
Mean 0.449
Std Dev 0.209
Values 10000
(h)
COMBINED TOT
0.128
0.824
5.0%
90.0%
5.0%
COMBINED TOT
Minimum 0.00427
Maximum 1.000
Mean 0.449
Std Dev 0.209
Values 10000
(i)
COMBINED TOT
Regression Coefficients
NA TOT DEV TRUNC
0.96
NA TOT SLR TRUNC
0.24
Coefficient Value

Figure 14g-i.

### 3.1.2 Risk assessment using basin means

*Risk profiles*

The frequency distribution of mean basin sub-catchment assets and threats data exhibited similar patterns to those derived for the northern Australia study area across sub-catchments (see Appendix A, Table 6b). Risk profiles were similarly derived as described above for analysis at sub-catchment level. The contrast in Development and SLR risk profiles to all aquatic ecosystem types combined, using basin means, is illustrated in Figure 15a & b and results are similar to those across sub-catchments (see Fig. 13a & b). Results show that risk from Development in 2010 is about 3 times greater than risk from SLR in 2100 (0.53 cf. 0.19). Development risks in 2010 to HCVAE99 assets using basin means were also about 23 times that of SLR rise risk in 2100 (0.0045 cf. 0.0002), with the overall combined risk being very small (< 0.005 or ~ 0.5%).

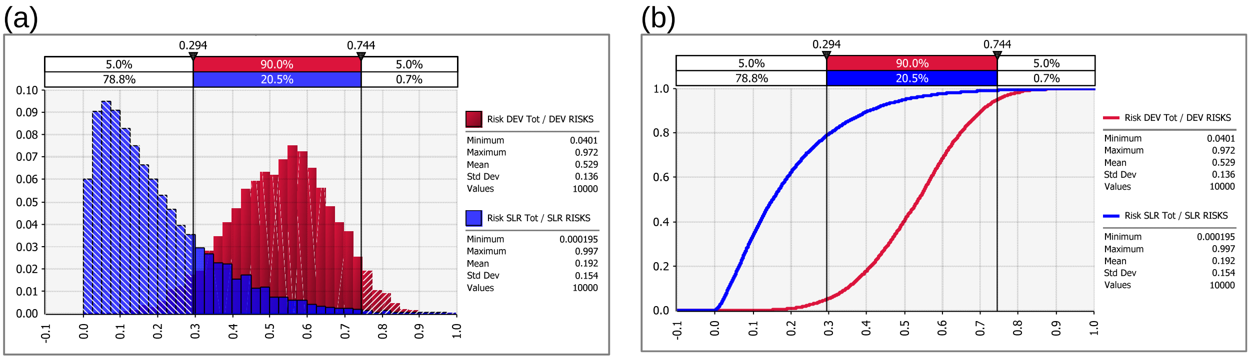



Figure 15a & b. Contrast in Development (red) and SLR (blue) risk profiles across northern Australia using mean basin values for aquatic ecosystem types combined. (a) Relative frequency distribution and (b) cumulative probability function. Similar risk profiles were developed for HCVAE99 assets using mean basin values.

*Uncertainty analysis*

Monte Carlo simulations (n=10,000) and sensitivity analysis were also undertaken on all mean basin risk profiles to ascertain their relative contributions to total risk. In contrast to the analysis across basins, sensitivity results using mean basin values show that all aquatic ecosystem types contributed equally to total Development risk (Fig. 16a-c). Riverine ecosystems contributed most to total SLR risk and, in contrast to previous analysis, Lacustrine ecosystems contributed more than Palustrine ecosystems (Fig. 16d-f). Overall, however, mean total Development and SLR risks are very similar. Additionally, sensitivity analysis (Figs. 16g-i) shows also that Development risk contributed slightly more than SLR risk to total combined risk to aquatic ecosystem types. Although the overall pattern of results using basin means are similar to those using sub-catchment data, these differences warrant further investigation. As with the previous analysis, the Development and SLR risks to HCVAE99 values were too small to warrant uncertainty analysis.

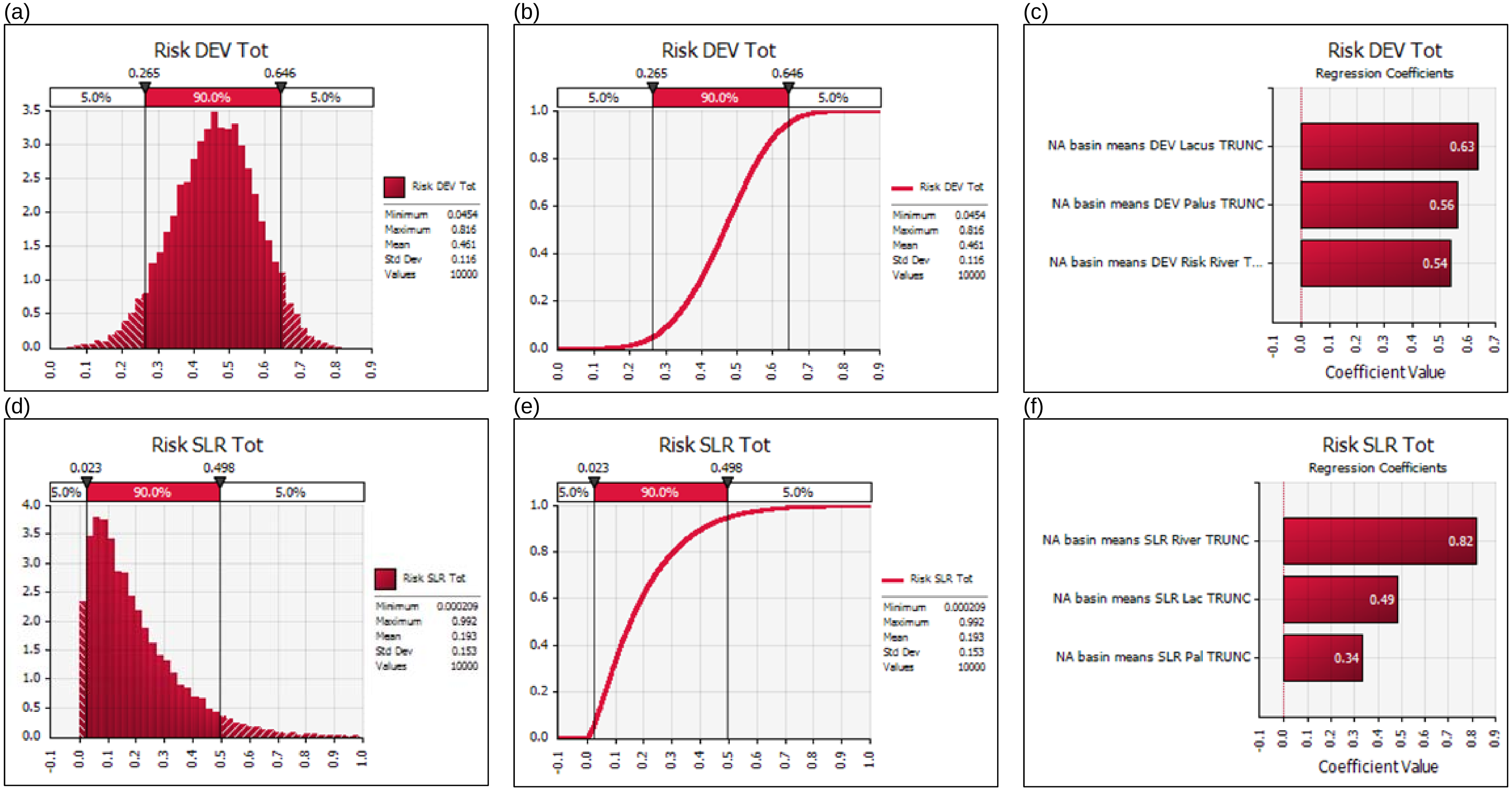



Figure 16a -i. Sensitivity analyses for (a-c) total Development risk, and (d-f) total Sea Level Rise (SLR) risk, to Riverine, Palustrine and Lacustrine aquatic ecosystems using mean basin values. (a & d) probability distribution functions (pdf), or total risk profiles, for Development and SLR1 risks, respectively. (b & e) cumulative probability functions for Development and SLR risks, respectively. (c & f) Tornado graphs showing which input variables contributed most to total risk. (g-i) Similarly for total combined risks (Development & SLR) to aquatic ecosystems.

(g) (h) (i)

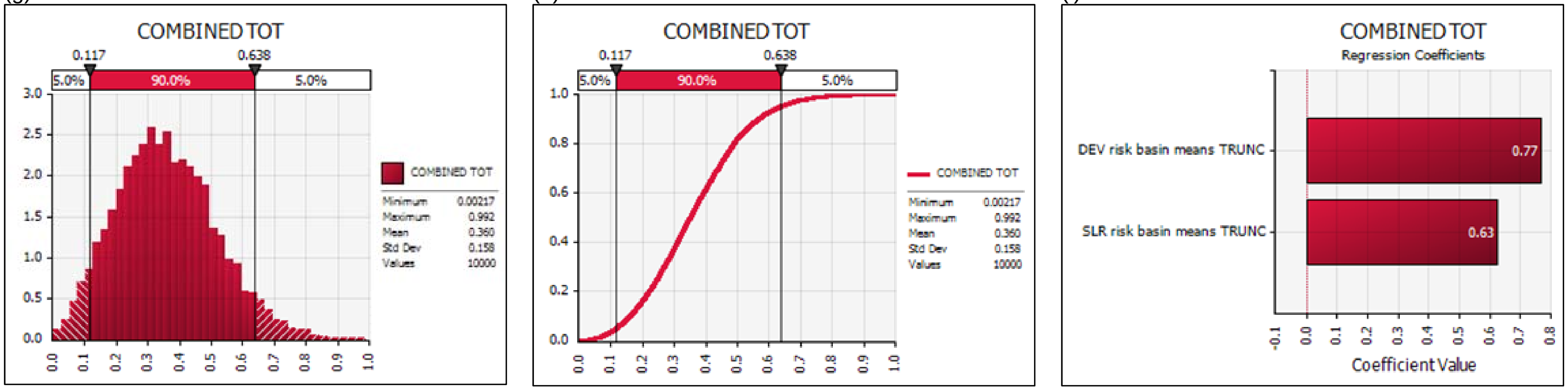



Figure 16g-i.

## 3.2 Basins flagged by jurisdictions

*Risk profiles by basins*

The above results suggest that using mean basin values should produce comparable risk results to more detailed sub-catchment analysis across basins, particularly when comparing total risks across aquatic ecosystem types, or when comparing combined risks from different risk factors. Hence, risks are now compared between basins using basin means.

Figure 17 is a Tornado graph that ranks the mean total Development risk to all aquatic ecosystems of AWRC basins in the study area, from highest (top) to lowest (bottom). The basins selected by the jurisdictions are highlighted in blue and the Finniss River basin is highlighted in orange. The basins most at risk from current development threats are the cluster in the southern GoC (Qld) and the Adelaide River basin close to Darwin (NT). In contrast, the basins least at risk from current development are the cluster in remote Arnhem Land (NT), the South and East Alligator River basins in Kakadu National Park, and the Moyle River basin far from anywhere.

Figure 18 ranks the mean total SLR risk to aquatic ecosystems of AWRC basins from highest to lowest. The basin most at risk is Mornington Inlet, being a small low-lying coastal basin. Whilst Sea Level Rise risk across the north is patchily distributed, the risk will most likely depend on the length of coastline that basins have in combination with the susceptibility of adjacent aquatic ecosystems prone to sea water inundation.

Figure 19 ranks the mean combined risk to aquatic ecosystems of AWRC basins from highest to lowest. Mornington Inlet retains first place due to its very high risk from SLR, whilst all previous basins with high Development risks remain clustered at the top.

Figure 20 ranks the mean total Development risks to HCVAE99 values of AWRC basins in the study area from highest (top) to lowest (bottom). Basins selected by the jurisdictions are highlighted in blue, and the Finniss River basin is in orange. Whilst the maximum risk value is low (<0.08), the Adelaide River basin particularly stands out above the rest followed by the adjacent Mary River basin.

Figure 21 ranks the mean total SLR risk to HCVAE99 assets of AWRC basins from highest to lowest, with the Mornington Inlet standing out above the rest. However, SLR risk values are too low to warrant meaningful comparisons.

Figure 22 ranks the mean combined risk to HCVAE99 assets of AWRC basins from highest to lowest, the Adelaide River standing out head and shoulders above the rest, and followed by the adjacent Mary River basin.

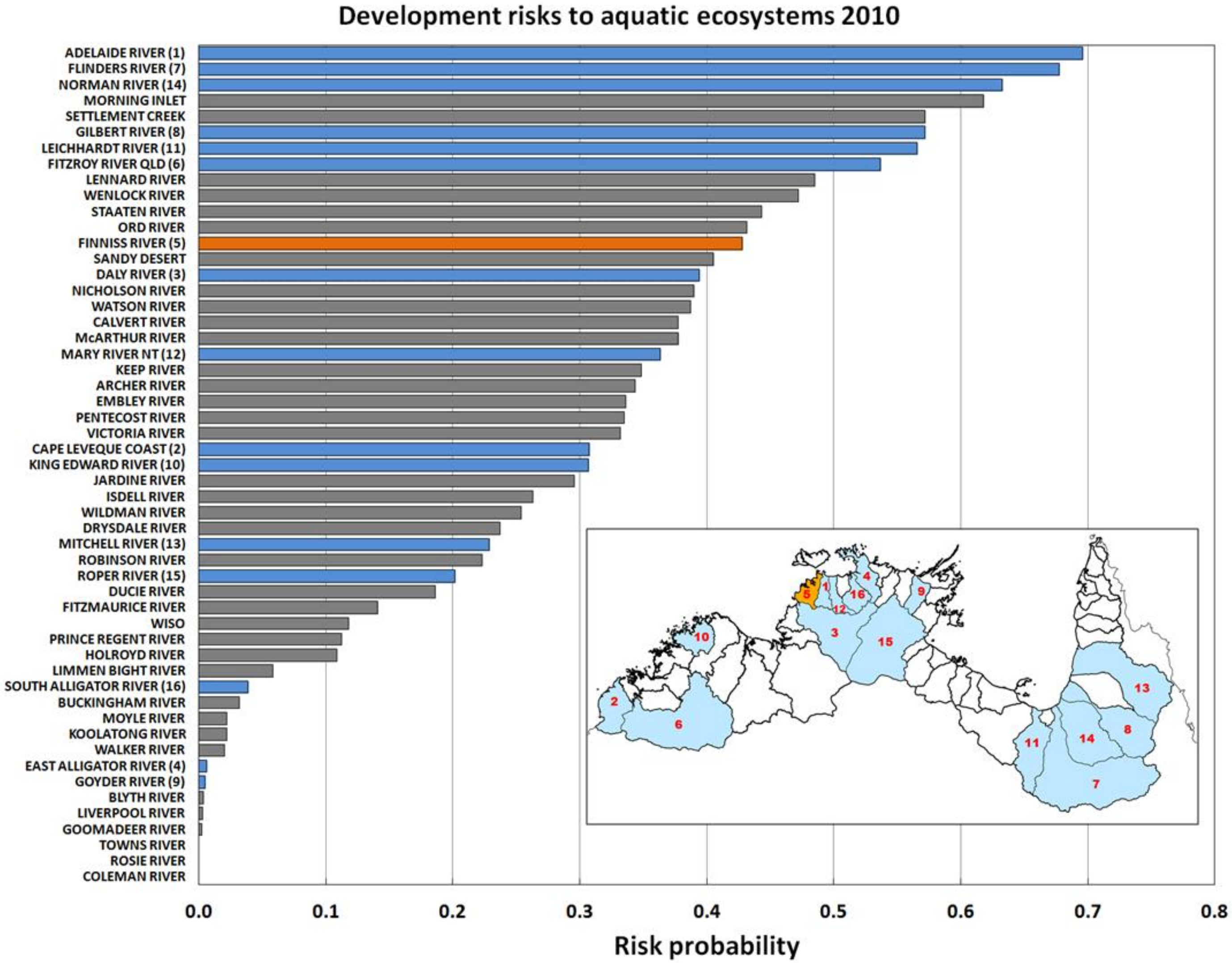



Figure 17. Tornado graph ranking Development risks to aquatic ecosystems (Kennard 2010) using sub-catchment means of AWRC basins. Basins flagged by jurisdictions are blue and the Finniss River basin is orange.

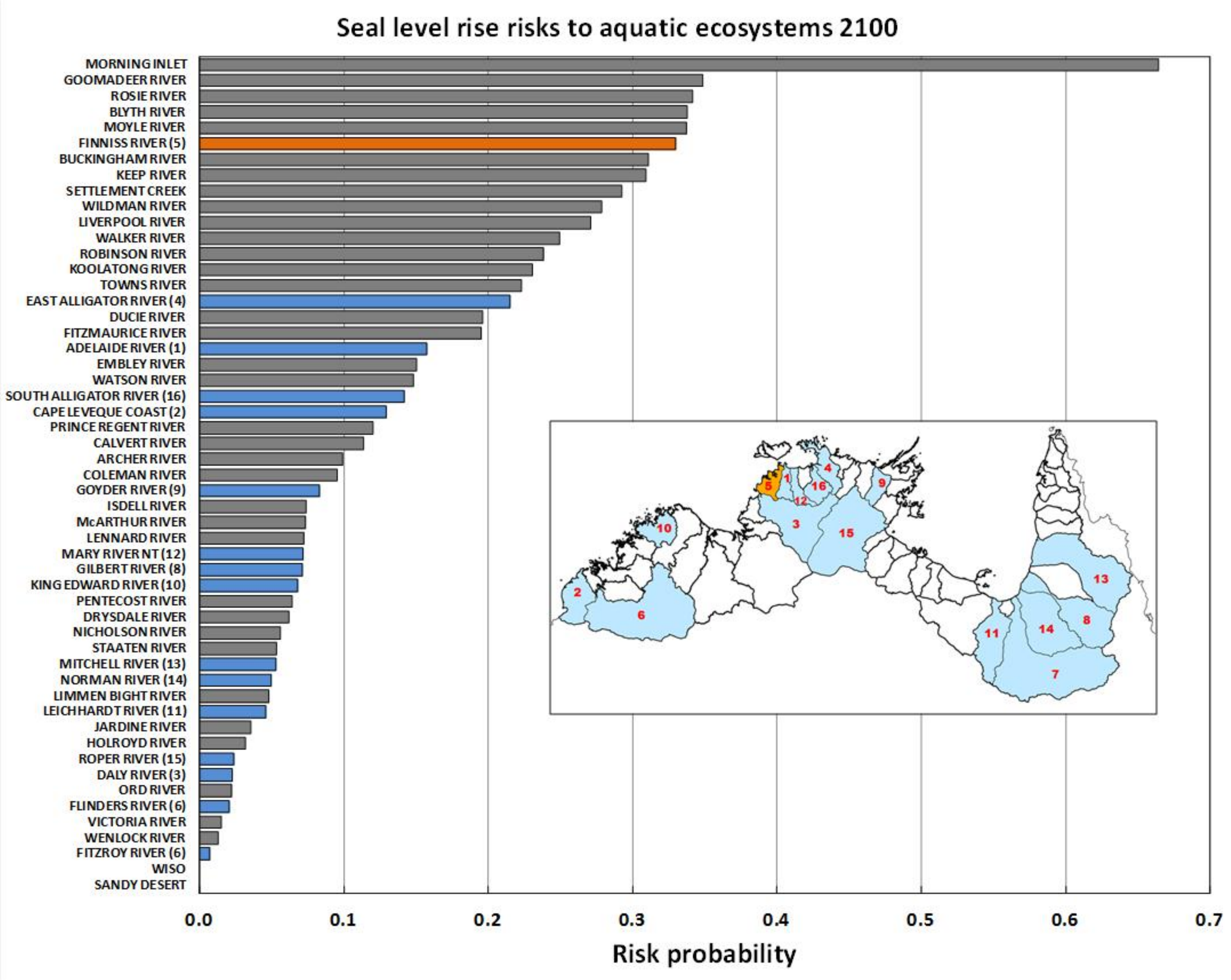



Figure 18. Tornado graph ranking Sea Level Rise (SLR) risks to aquatic ecosystems (Kennard 2010) using sub-catchment means of AWRC basins. Basins flagged by jurisdictions are blue and the Finniss River case study basin is orange.

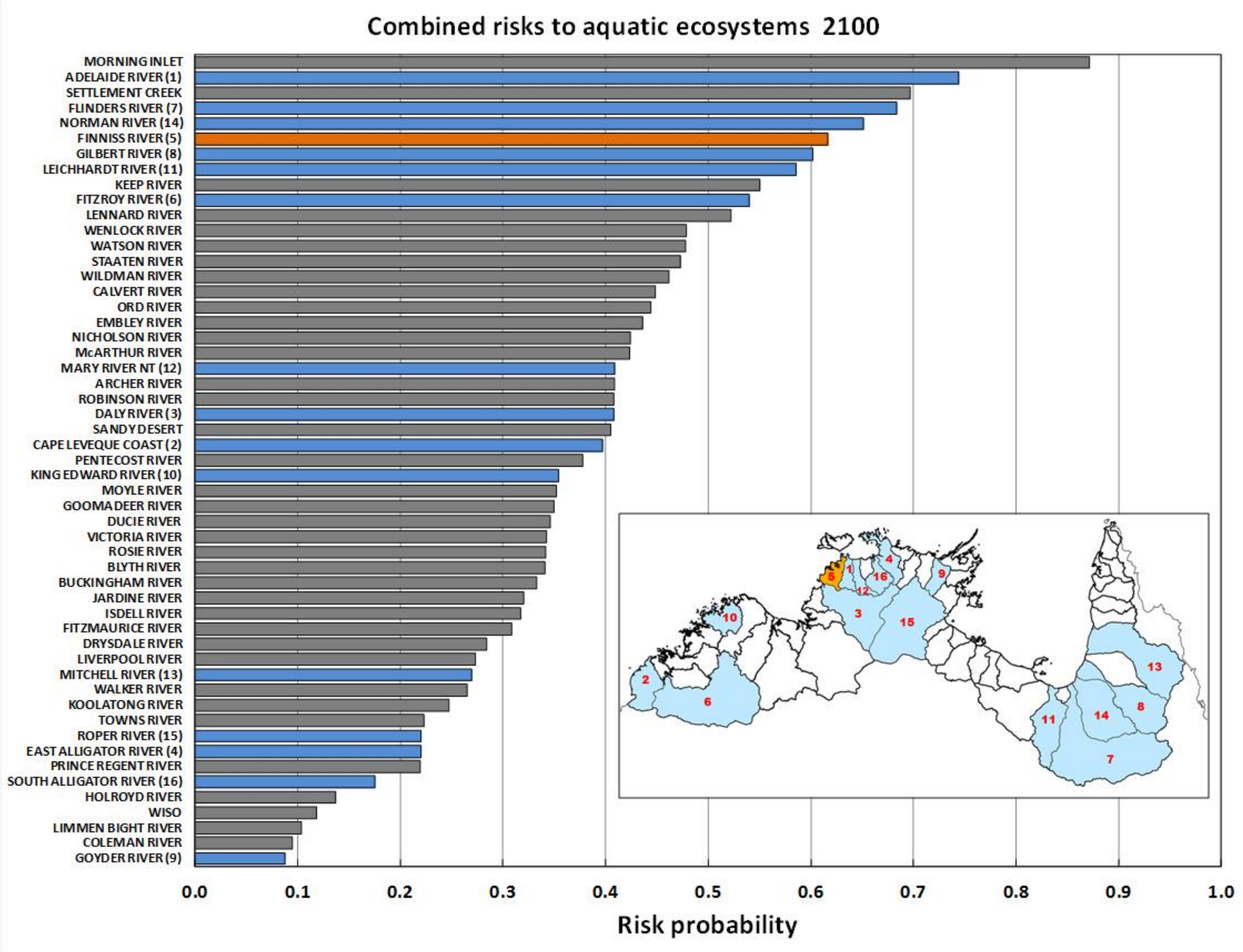



Figure 19. Tornado graph ranking combined (Development & SLR) risks to aquatic ecosystems (Kennard 2010) using sub-catchment means of AWRC basins (assumes that Development risks will be constant for 89 years). Basins flagged by jurisdictions are blue and the Finniss River basin is orange

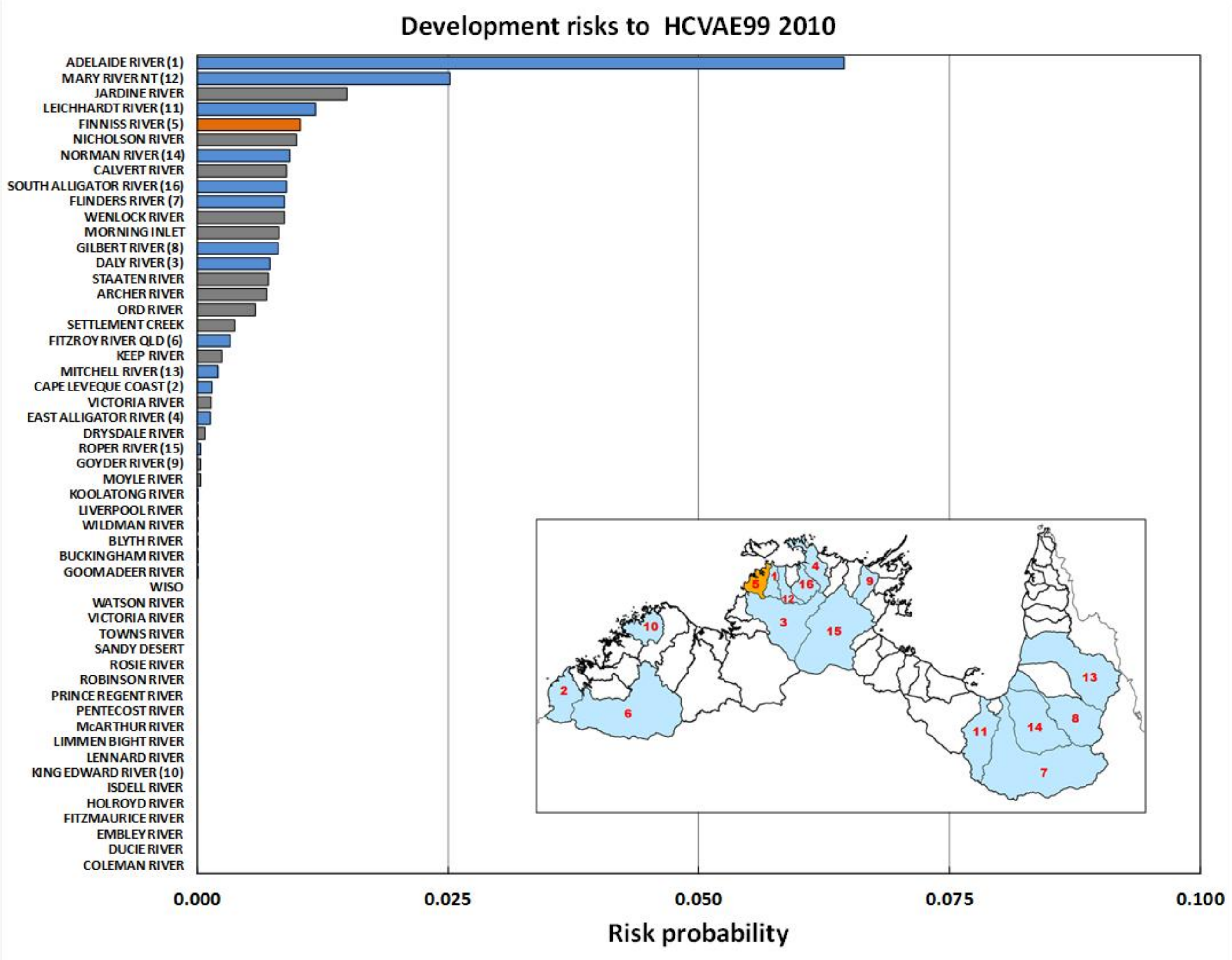



Figure 20. Tornado graph ranking Development risks to HCVAE99 assets (sum of all criteria met at the 99th percentile; Kennard 2010) using sub-catchment means of ARWC basins. Basins flagged by jurisdictions are blue and the Finniss River basin is orange.

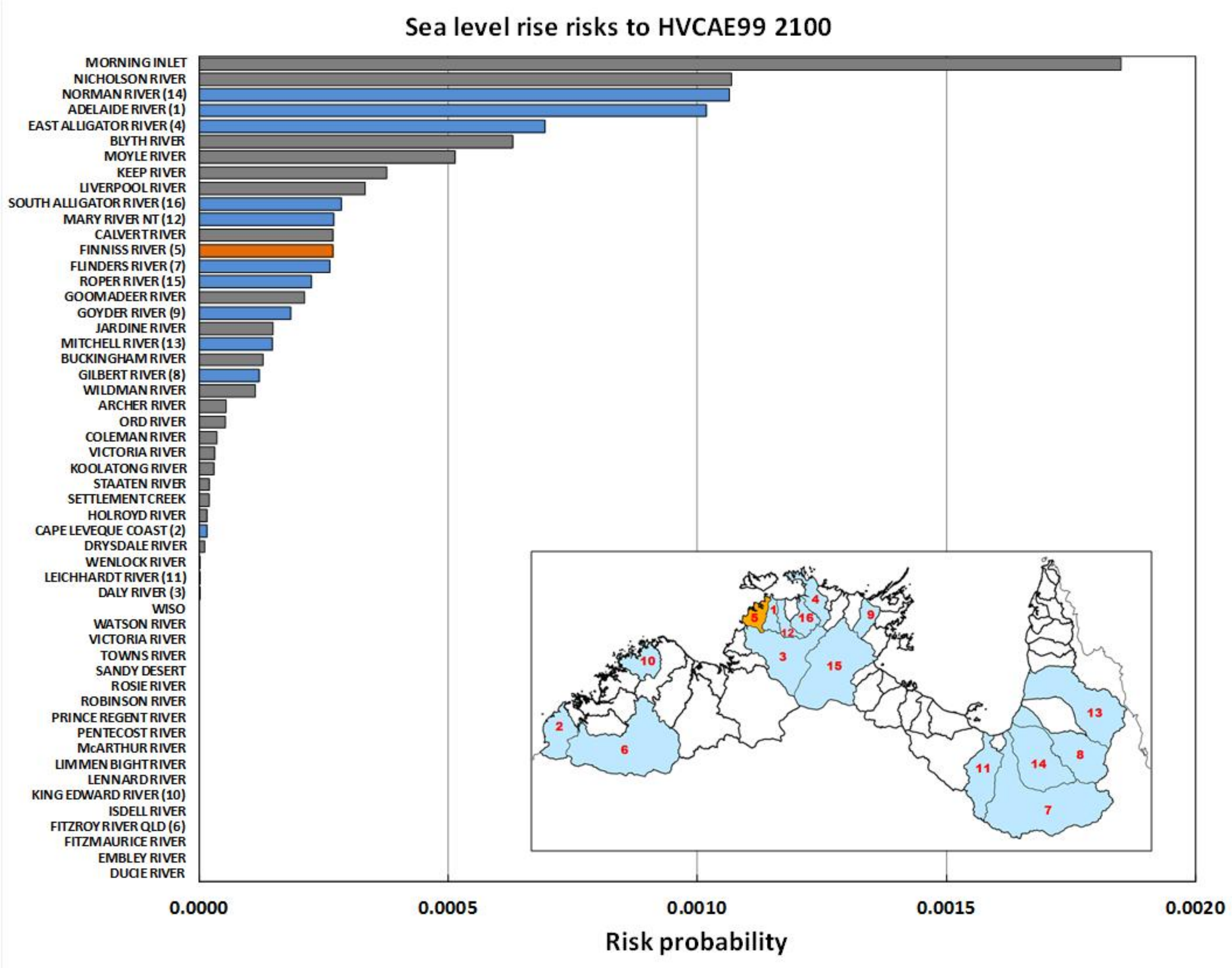



Figure 21. Tornado graph ranking Sea Level Rise (SLR) risk to HCVAE99 assets using sub-catchment means of AWRC basins. Basins flagged by jurisdictions are blue and the Finniss River basin is orange.

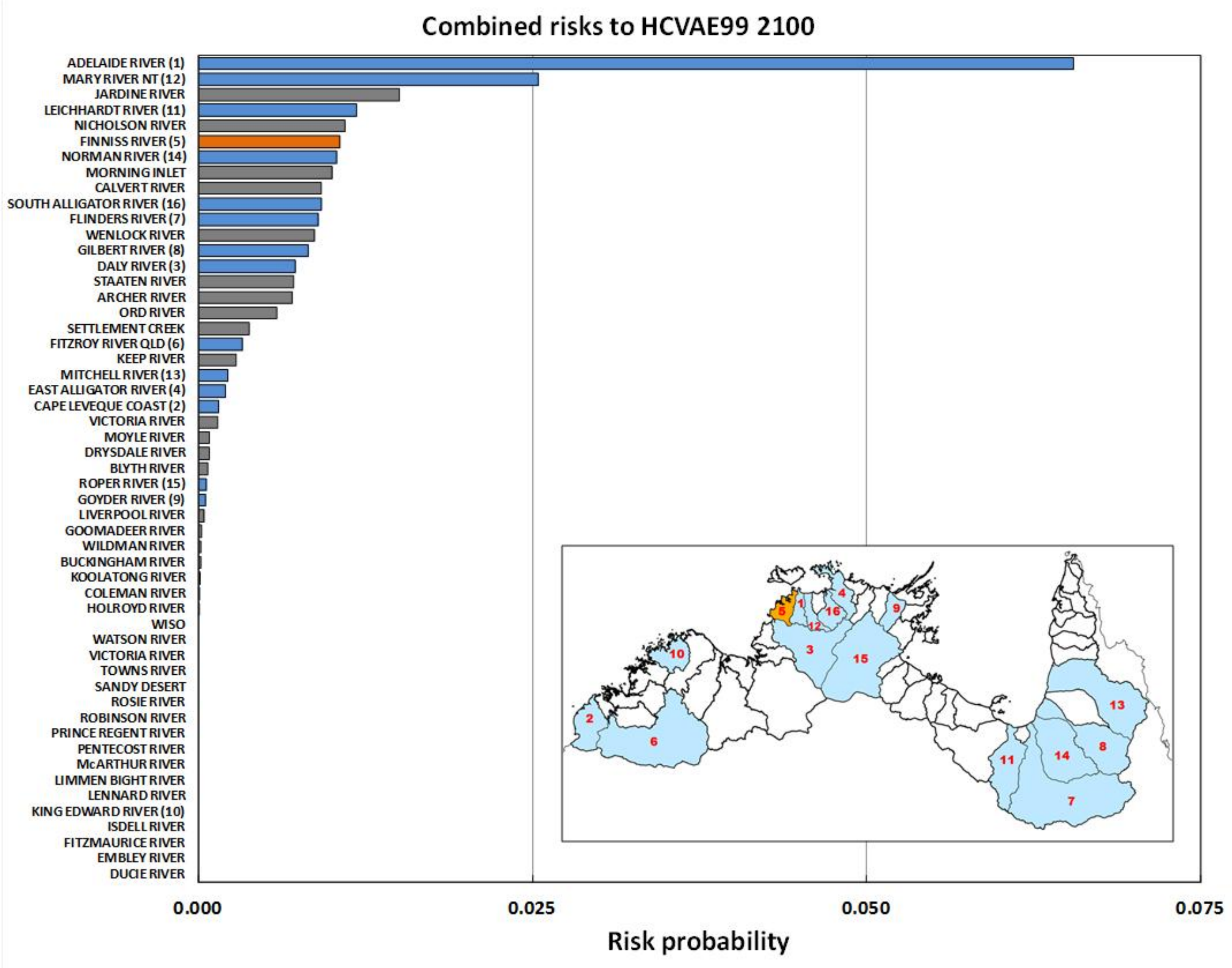



Figure 22. Tornado graph ranking combined (Development & SLR) risks to HCVAE99 assets using sub-catchment means of AWRC basins. Basins flagged by jurisdictions are blue and the Finniss River basin is orange.

## 3.3 Fine-scale comparison of basins with contrasting land use

### 3.3.1 The Norman South Alligator River basins

*Spatial distribution of basin assets and risks*

The distribution and extent of Riverine, Palustrine and Lacustrine aquatic ecosystems in the Norman River basin are illustrated in Figures 23a & b, and that for HCVAE99 assets in Figure 23c. The predominant aquatic ecosystem is Riverine.

Total Development and SLR risks to aquatic ecosystems in the Norman River basin are illustrated in Figures 24a & b, respectively, and those for HCVAE99 assets in Figure 24c & d, respectively. Development risk is extensive throughout the basin and, in contrast, SLR risk is confined to the mouth of the Norman River and associated small coastline.

In contrast, the South Alligator River basin inside Kakadu National Park has extensive aquatic ecosystems of all types (Figs. 25a & b) and, additionally, has more extensive (with a higher rating) of HCVAE99 assets (Fig. 25c). Development risk to aquatic ecosystem assets is low (Figure 26a), and more extensive in the south-west corner of the basin reflecting previous land use (cattle grazing) in Kakadu stage 3. The risk to aquatic ecosystems from a 1m SLR projection in 2100 is high to medium, and confined to the northern section of the basin close to the river mouth. The risk from Development to aquatic ecosystems and HCVAE99 assets is low overall (Figs 26a & c, respectively) and, similarly, for the risk from SLR (Fig. 26b & d).

*Risk profiles*

All risk profiles for Development and SLR threats to each aquatic ecosystem type, and to HCVAE99 assets, are summarised in Appendix A (Table 6c). A comparison of the Development and SLR risk profiles to aquatic ecosystems for the Norman River and South Alligator River basins is illustrated in Figures 27a & b and 27c & d, respectively. Risk profiles were derived by Monte Carlo simulation (n=10,000) as outlined in previous sections. The mean risk from Development is about 19 times greater in the Norman River basin than the South Alligator River basin (mean 0.503 cf. 0.026). Additionally, Development risks in the Norman River basin are spread out over a greater range of higher values than the South Alligator River basin. Whilst the spread of SLR risk is similar between basins, in contrast the South Alligator River basin exhibits a handful of very high values. The risk from SLR is about 4 times greater in the South Alligator River basin than the Norman River basin (mean 0.164 cf. 0.044).

The risk to HCVAE99 assets from Development in the Norman River basin is twice that of the South Alligator River basin (mean 0.013 cf. 0.008). In contrast, SLR risk is 13 times greater in the South Alligator River basin than the Norman River basin (mean 0.026 cf. 0.002).

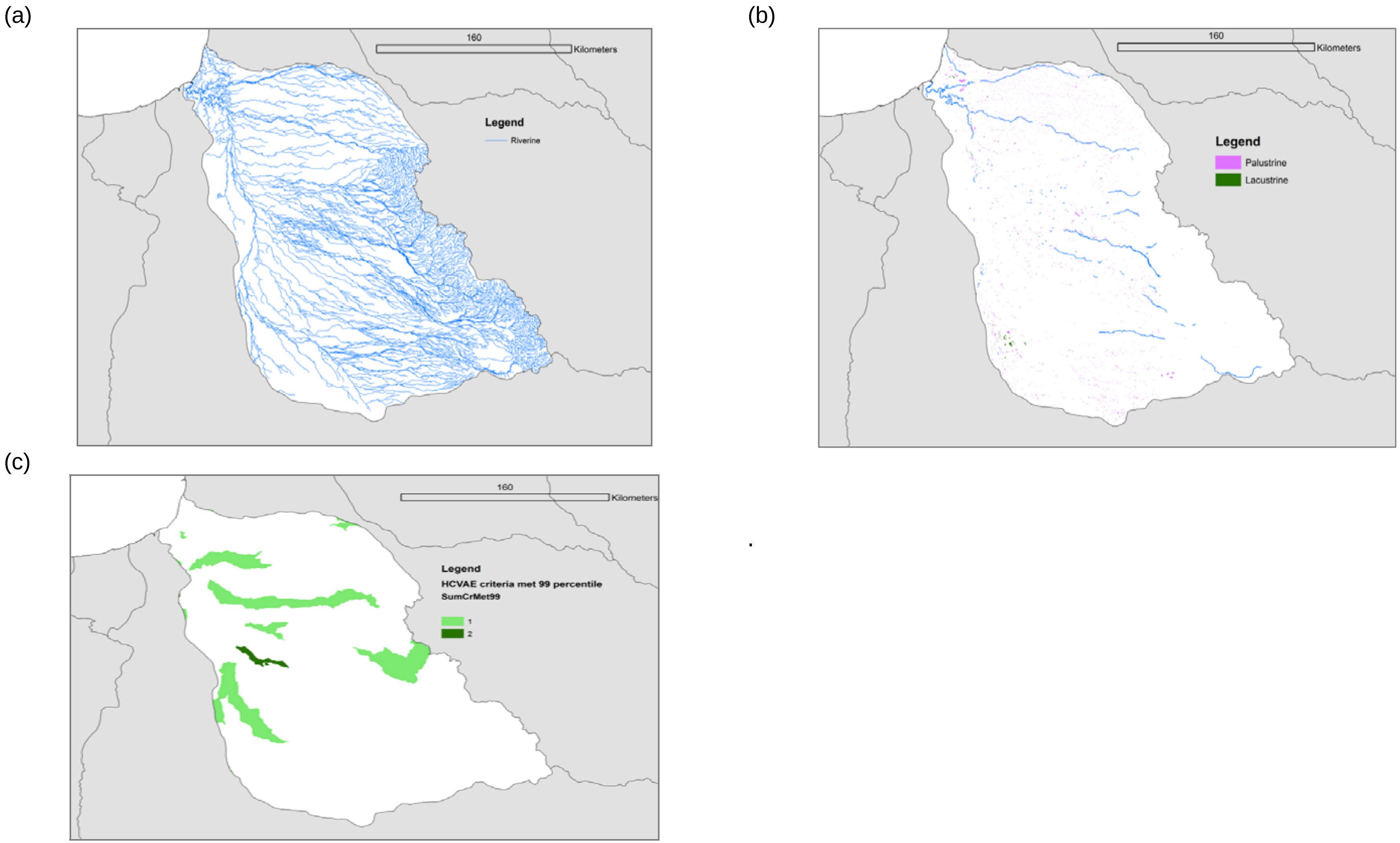



Figure 23a-c. The distribution of (a) Riverine, and (b) Palustrine and Lacustrine, aquatic ecosystems, in the Norman River basin (the main stream channels are blue). (c) Similarly, for HCVAE99 assets ((the sum of all criteria met at the 99th percentile; Kennard 2010).

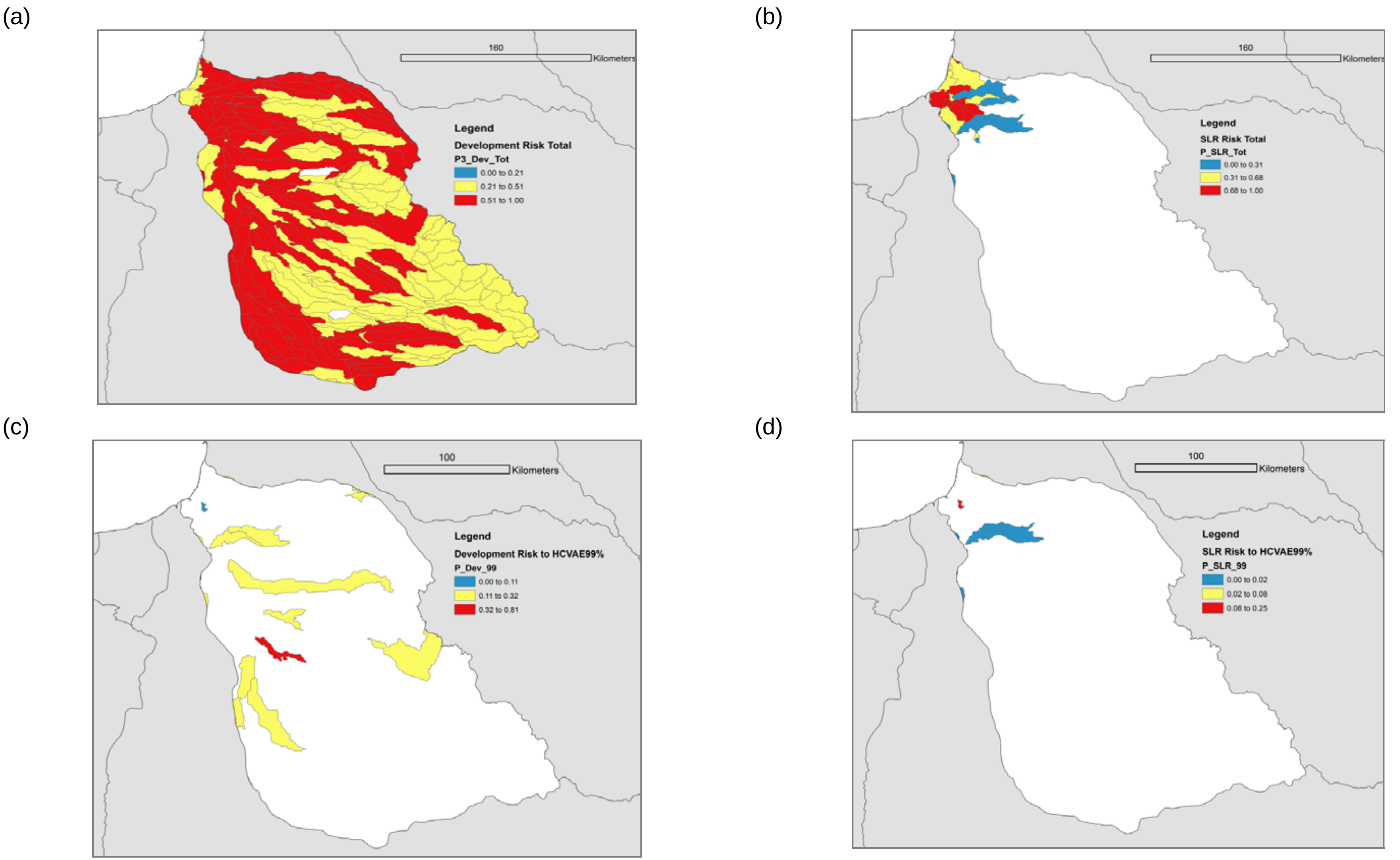



Figure 24a-c. Risk to aquatic ecosystems in the Norman River basin from (a) Development (2010) and (b) Sea Level Rise (SLR; 2100). Similarly, risks to HCVAE99 assets from (c) Development (2010) and (d) Sea Level Rise (2100).

(a)

(b)

(c)

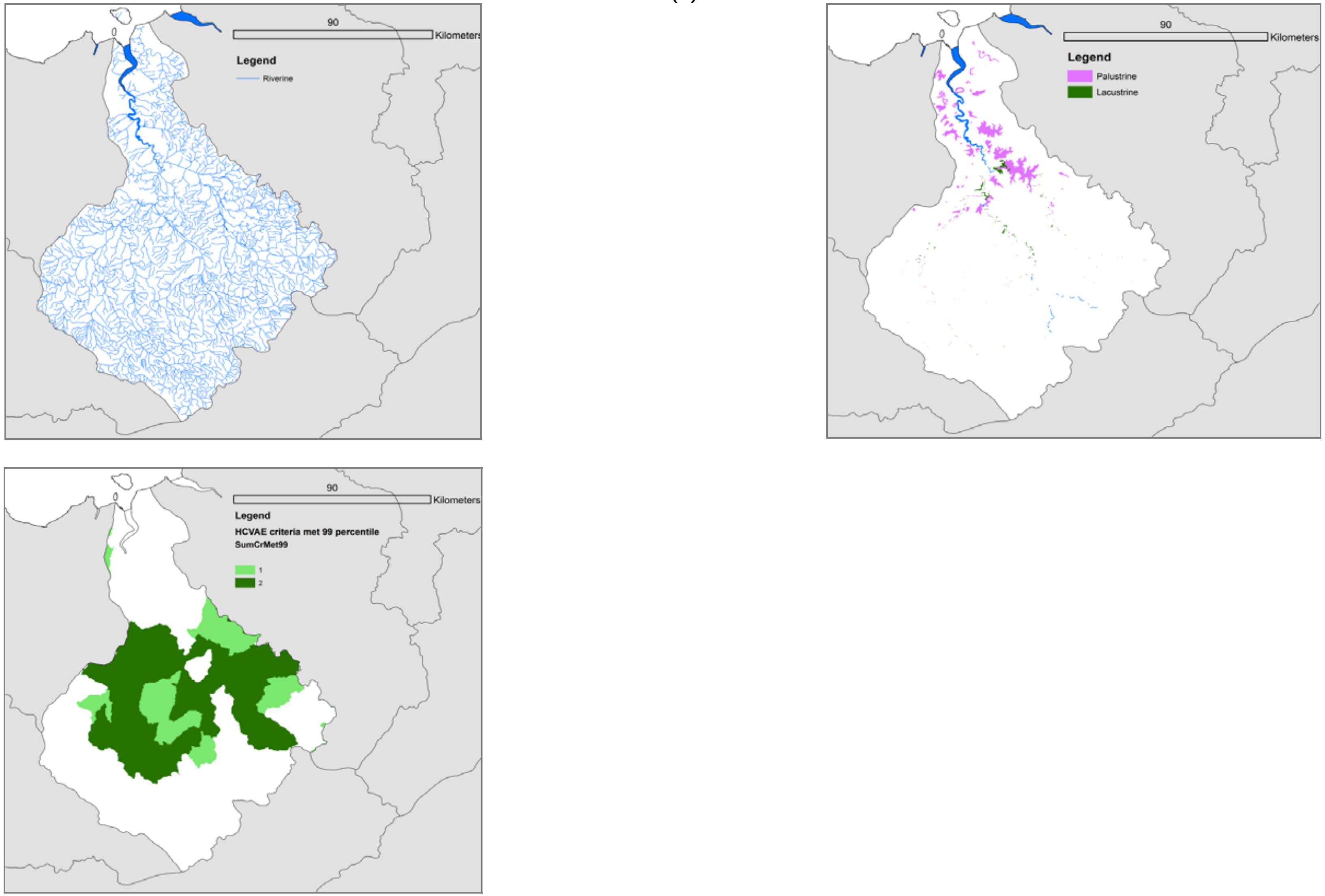



Figure 25a-c. The distribution of (a) Riverine, and (b) Palustrine and Lacustrine, aquatic ecosystems in the South Alligator River basin. (c) Similarly for HCVAE99 assets (the sum of all criteria met at the 99th percentile; Kennard 2010).

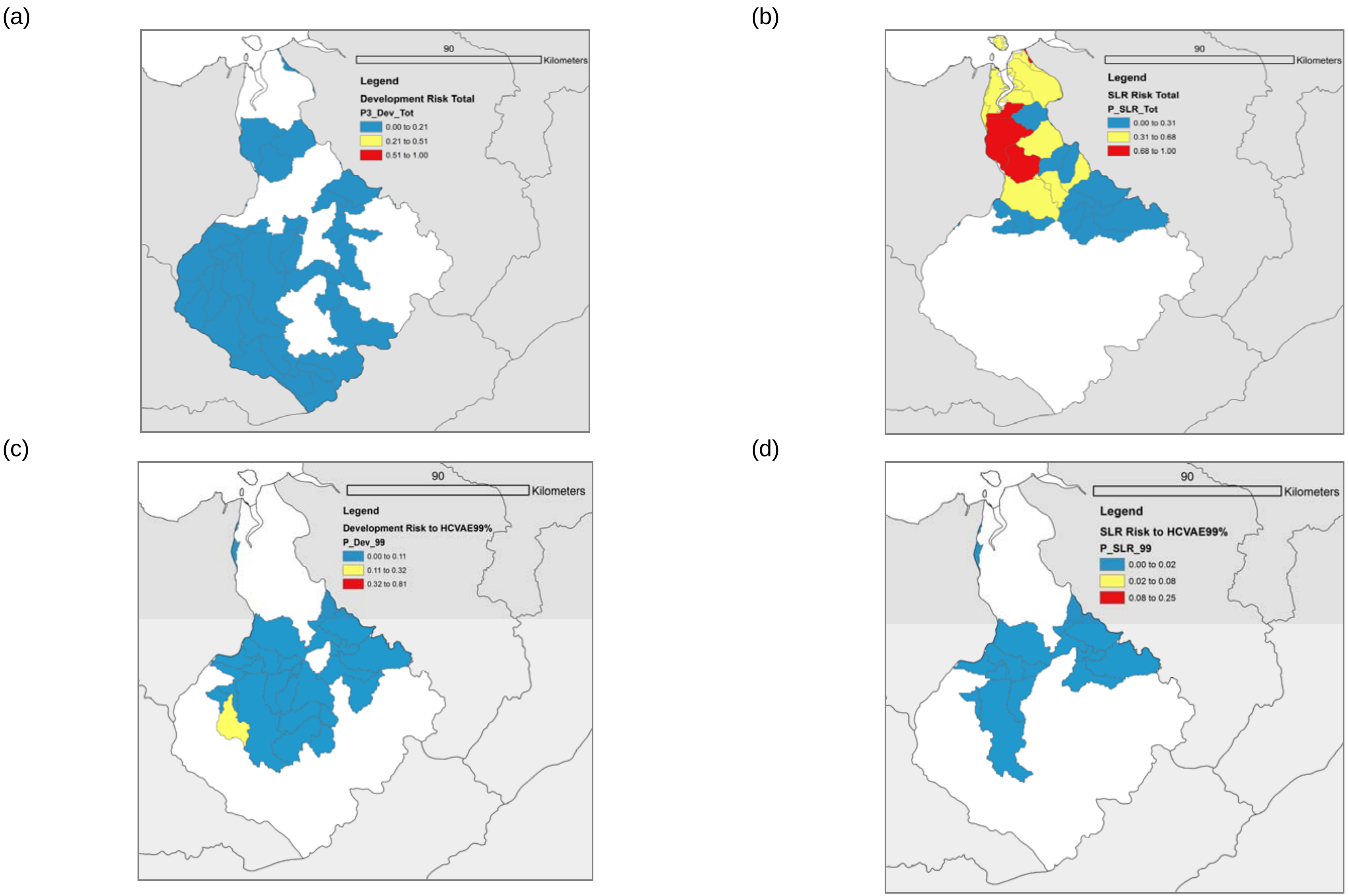



Figure 26a-c. Risk to aquatic ecosystems in the South Alligator River basin from (a) Development (2010) and (b) Sea Level Rise (SLR). Similarly, risks to HCVAE99 assets from (a) Development (2010) and (b) Sea level rise (2100).

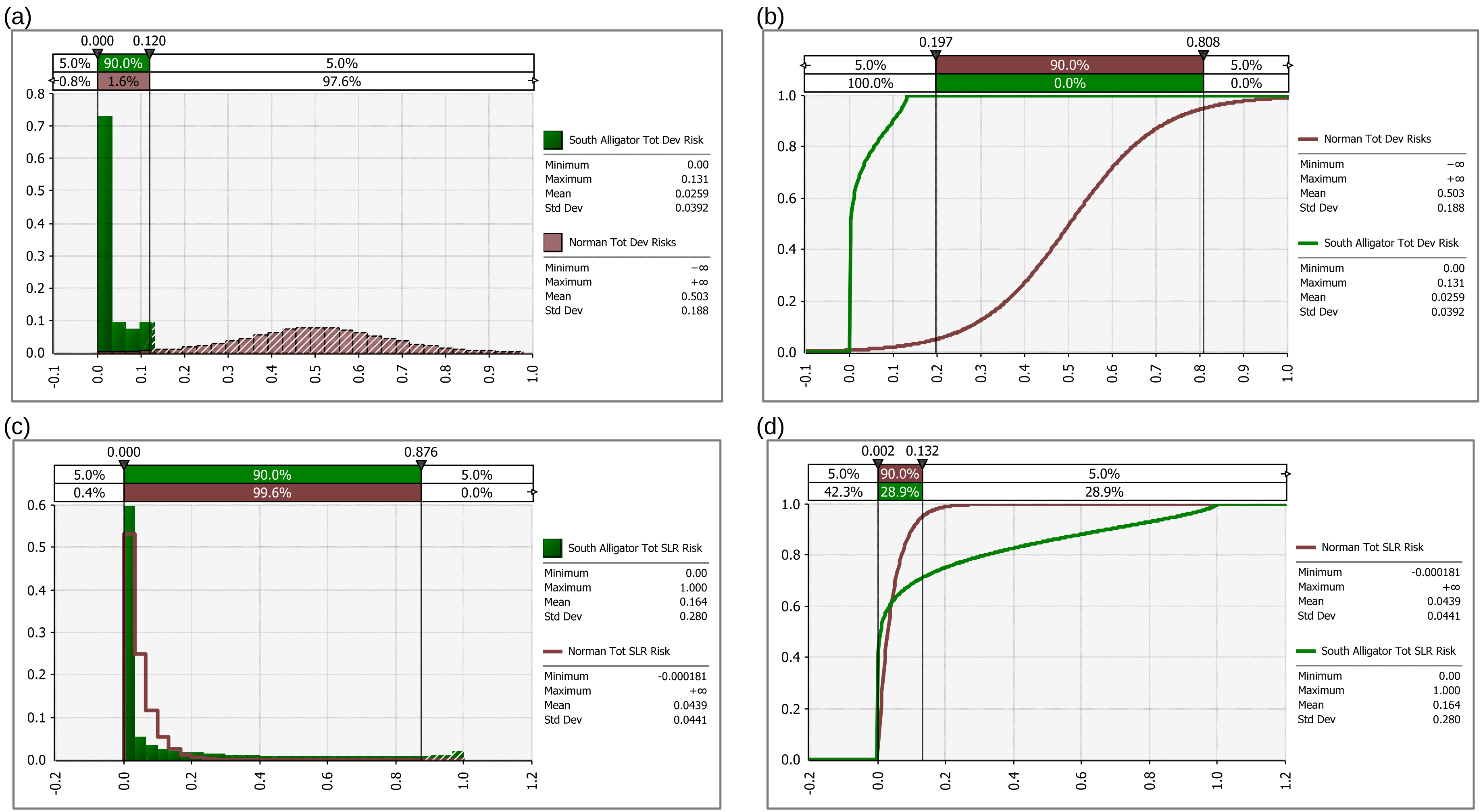



Figure 27a-d. Comparison of Development and Sea Level Rise (SLR) risk profiles to aquatic ecosystems for two basins with contrasting land uses (the South Alligator River basin in Kakadu National Park c.f. the Norman River basin in the Southern Gulf of Carpentaria). “Best Fit” statistical functions (Palisade 2010) were derived from sub-catchment data within basins. (a) Relative frequency distribution and (b) cumulative probability function (South Alligator R basin green, Norman R basin brown) for Development risks. (c & d) Similarly for SLR risk.

## 3.4 Finniss River case study

### 3.4.1 Quantitative Relative Risk Model

*Spatial distribution of basin assets and risks*

The sub-catchments (n=53) of the Finniss River basin are shown in Figure 28a. The distribution and extent of Riverine, Palustrine and Lacustrine aquatic ecosystems are illustrated in Figure 28b, and includes foreshore tidal mudflats and mangroves. The predominant aquatic ecosystem type is Riverine and, in contrast, Lacustrine ecosystems are rare and small in size. The distribution of HCVAE99 assets is mapped in Figure 28c and, whilst extensive in the basin, only one criteria was met throughout.

The CDI (not re-scaled to northern Australia) and the FRDI in the Finniss River basin are illustrated in Figures 29a & b, respectively, showing that most disturbances are catchment based and occur in the southern and north-eastern parts of the basin. Total Development risk to aquatic ecosystems is mapped in Figure 29c, and that for total SLR risk in Figure 29d. High to medium Development risks are extensive, reflecting significant catchment disturbances. High to medium SLR risks are also extensive, reflecting the occurrence of extensive low-lying coastal wetlands associated with the Finniss River.

Where HCVAE99 assets occur in the Finniss River basin, risk from total Development is rated as low to medium (Figure 30a) and, in contrast, the risk from a 1m SLR is rated as very low (Fig. 31b).

*Risk profiles*

All risk profiles for Development and SLR threats to each aquatic ecosystem type, and to HCVAE99 assets, are summarised in Appendix A (Table 6d). A comparison of Development and SLR risk profiles to aquatic ecosystems in the Finniss River basin is illustrated in Figures 31a & b. The combined risk profile is shown in Figure 31c. The risks from Development and SLR are similar (0.38 cf. 0.36, respectively) and relatively high, and both exhibit similar risk profiles (i.e. a "U"- shaped Beta-general pdf). The combined risk is therefore even higher (0.60), and the shape of the risk profile is highly skewed towards 1.0, possibly reflecting a handful of very small coastal sub-catchments susceptible to sea level rise.

*Uncertainty analysis*

Monte Carlo simulations (n=10,000) and sensitivity analysis were also undertaken to ascertain the relative contributions of each risk factor to the combined risk to aquatic ecosystems. Results show that Development and SLR risks contributed similar amounts to the combined risk (0.72 cf. 0.60 respectively, Fig. 31d). The mean risks to HCVAE99 assets from Development and SLR were insignificant, and so do not warrant uncertainty analysis (0.01 & 0.0003, respectively).

(a)

(b)

(c)

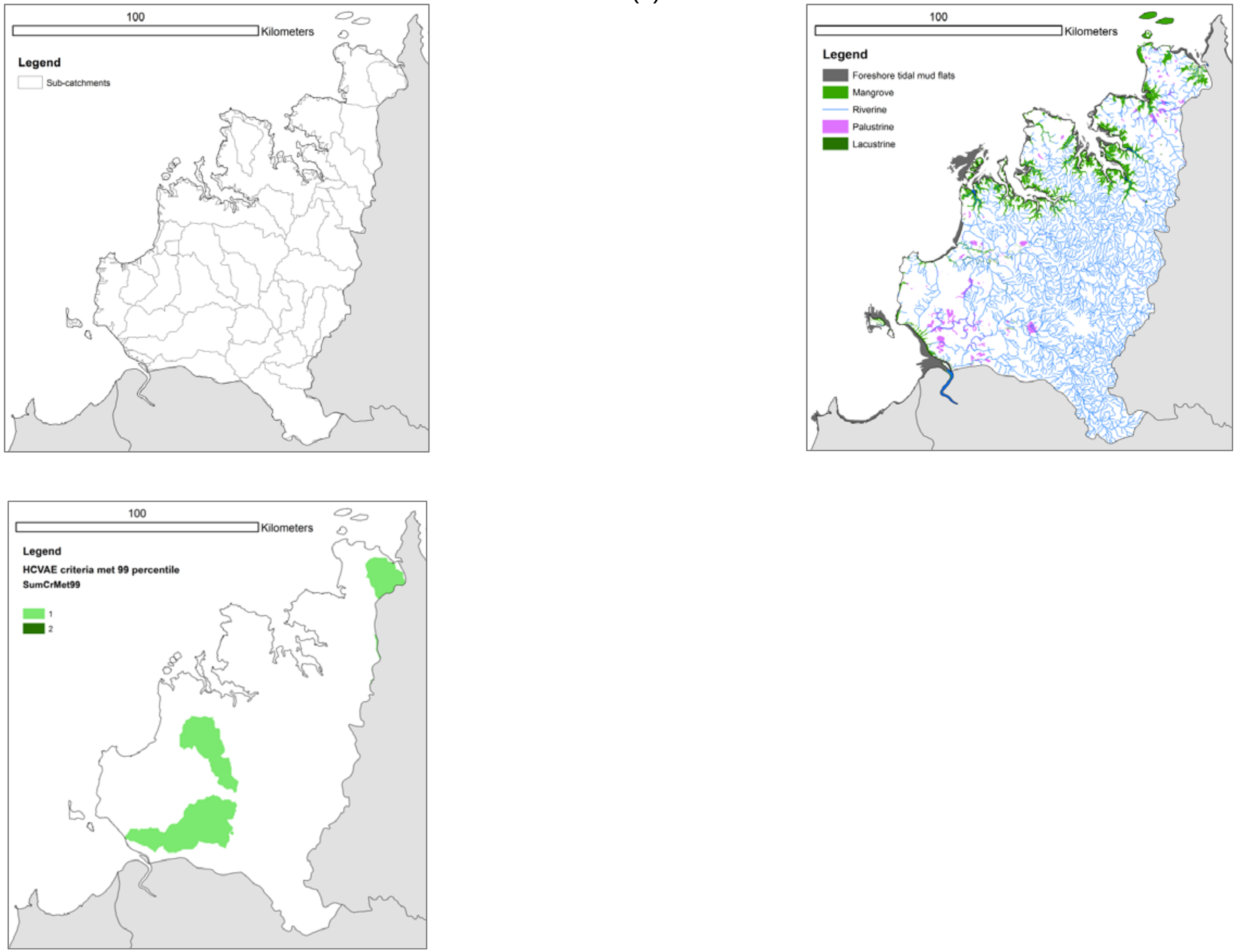



Figure 28a-c. The distribution of (a) Riverine ecosystems, and (b) Palustrine and Lacustrine ecosystems, in the Finniss River basin (foreshore tidal & mangrove habitats are shown also). (c) The distribution of HCVAE99 assets (sum of all criteria met at the 99th percentile; Kennard 2010).

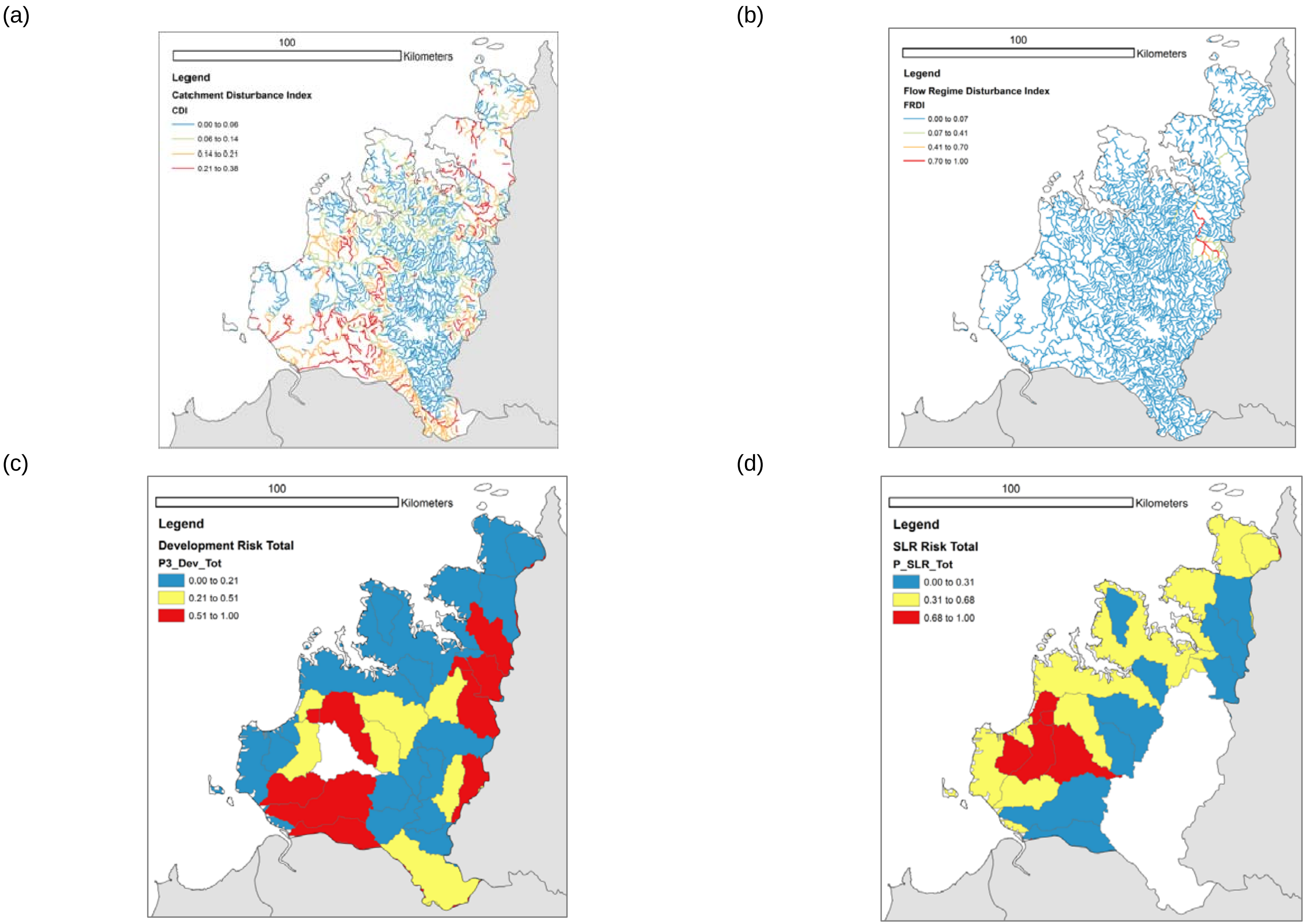
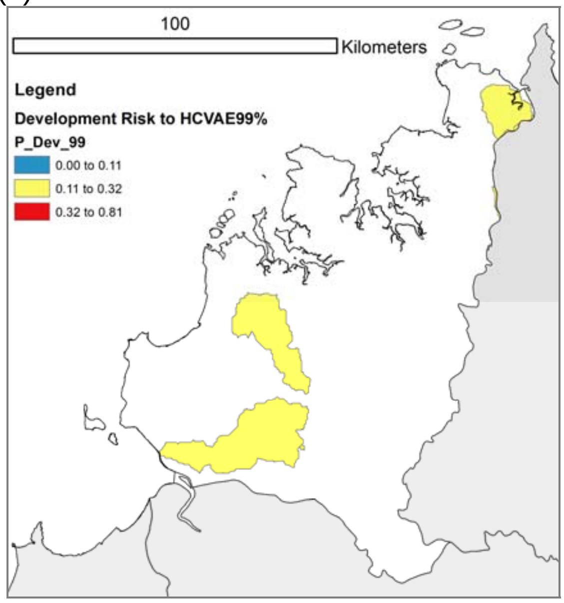



Figure 29a-d. Distribution of (a) Catchment Disturbance Index (CDI) values, and (b) Flow Regime Disturbance Index (FRDI) values, in the Finniss River basin. The distribution of (c) total Development and (d) Sea Level Rise (SLR) risks to aquatic ecosystems.

(a)




(b)

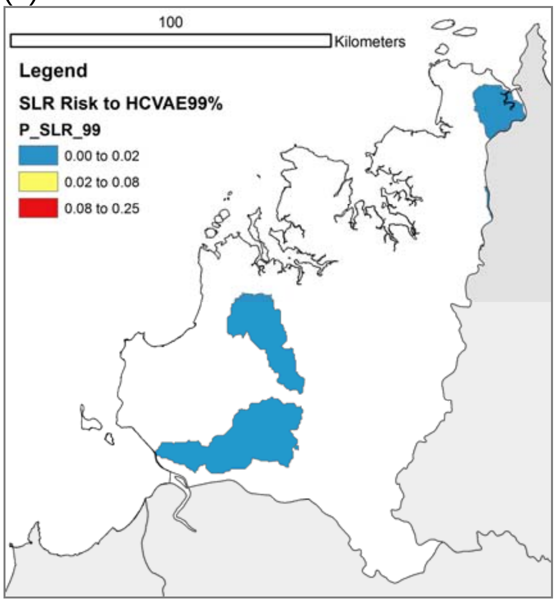



Figure 30a & b. The distribution of (a) total Development risk to HCVAE99 assets in the Finniss River basin, and (b) that for a 1m Sea Level Rise (SLR) risk.

### 3.4.2 Comparison of RRM approaches

*The NAWFA study area*

The combined risk (Pc) to aquatic ecosystems from Development and SLR risks in each of the 15 basins derived in this study were compared to the Total Relative Risk Rank (TRR) derived in section 1 using regression analysis. The TRR scores were first normalised to their maximum value to facilitate comparison with the mean sub-catchment probability values derived here for each basin. With the exclusion of one outlier (Mitchell River basin), the relationship is significant and non-linear (Fig. 32a). Hence, irrespective of the fact that the two methods use very different assessment pathways and complex assessment endpoints, the results suggest that, overall, they will produce similar outcomes at the basin level although there will likely be exceptions. This is highlighted in Figure 32b, which compares the risk rank scores of basins using the two risk assessment methodologies. Major differences occur in the Mitchell River, King Edward River, Finniss River and Norman River basins.

*The Finniss River basin*

The spatial units used to define relative risk regions in the Finniss River basin were similar but slightly different to the sub-catchment units used here. Hence mean values derived only from matching spatial units were used to compare the two different risk assessment methodologies, and so are not directly comparable to values in Fig. 32b. The relative risk scores across risk sub-regions (n=52) in the basin were first normalised to their maximum value to facilitate comparison with the mean sub-catchment probability values derived here. Results for three high level risk assessment endpoints derived by the rank-based RRM (Bartolo et al. 2012)

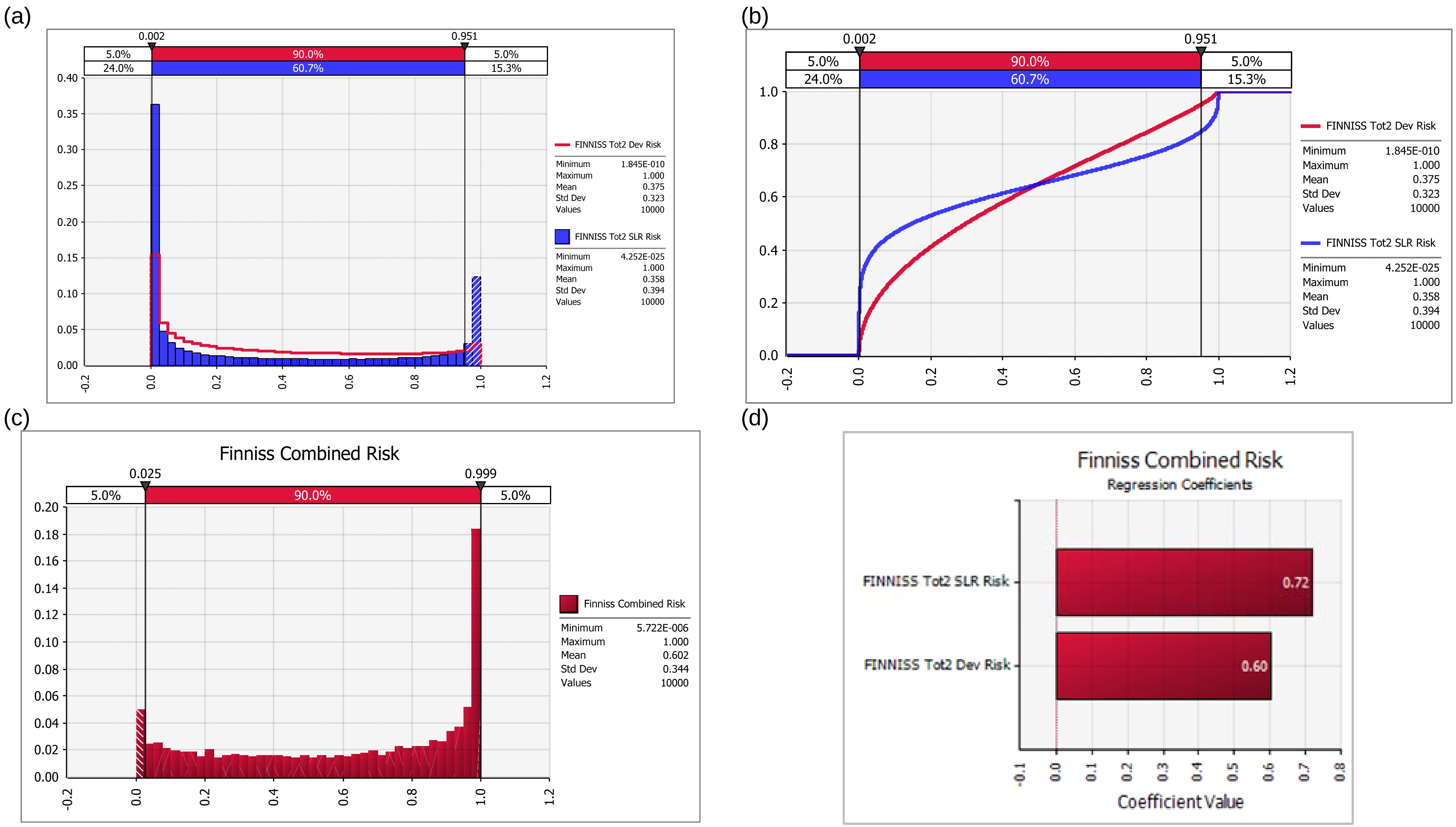
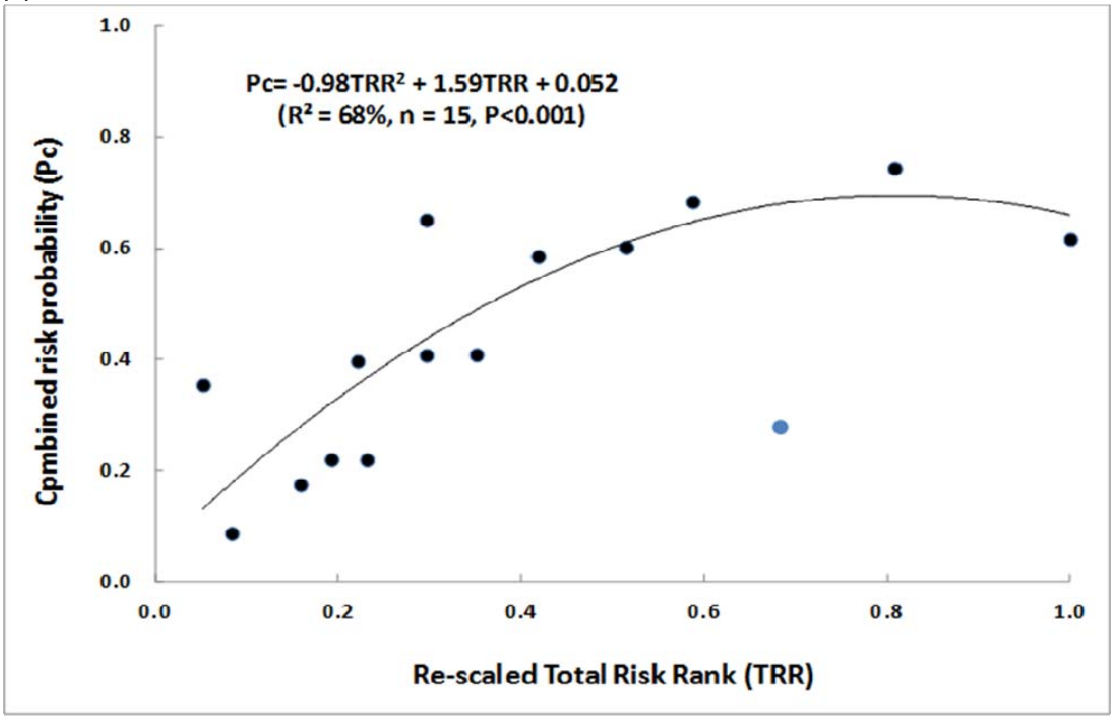



Figure 31a-d. Comparison of Development and Sea Level Rise (SLR) risk profiles to aquatic ecosystems for the Finniss River basin. (a) Relative frequency distribution and (b) cumulative probability function for Development (red) and a 1m SLR (blue) risks. (c) Combined risk profile (pdf), and (d) Tornado graph showing the relative contributions of Development and SLR risks to the combined total.

(a)




(b)

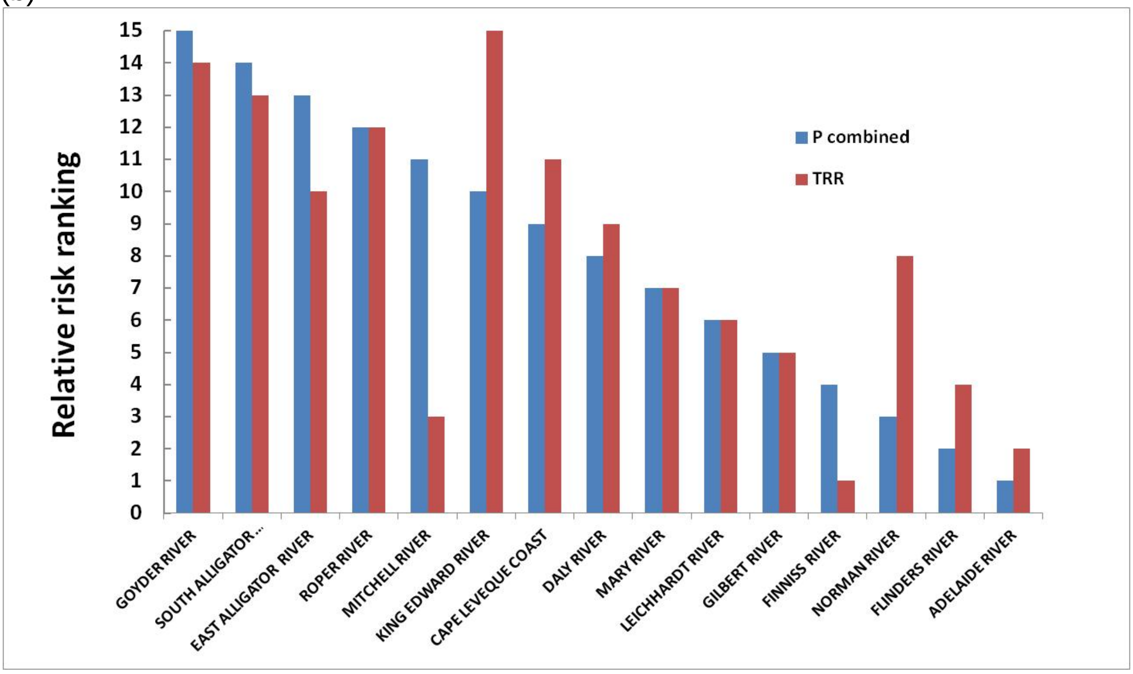



Figure 32a & b. (a) Regression relationship between the combined risk probability (Development & SLR) and the re-scaled (to 1.0) Total Risk Rank (TRR) across catchments selected by jurisdictions (less the Fitzroy River basin, WA). The Mitchell River basin is an outlier and excluded (blue point). (b) Comparison of risk rank scores of basins using the two risk assessment methodologies. Major differences occur in the Mitchell River, King Edward River, Finniss River and Norman River basins.

and the quantitative method developed here are, overall, very similar (Table 4) and, in combination with the preceding analysis, suggests that both methodologies could be used in a complimentary approach in a risk assessment process given that they have different strengths and weaknesses.

Table 4. Comparison of Development and SLR risks in the Finniss River basin (NT) derived from the rank-based Relative Risk Model of Bartolo et al. (2012) and the quantitative method developed here. Mean values of relative risk scores across 52 risk regions in the basin were normalised to their maximum value in order to compare with the mean sub-catchment probability values reported here (n=53).

| Risk assessment endpoint | TRIAP RRM | Revised RRM |
| --- | --- | --- |
| Sea Level Rise | 0.29 | 0.33 |
| Development surrogate (RDI) | 0.49 | 0.43 |
| Total combined risk | 0.42 | 0.53 |

## 3.5 Climate change risk to biodiversity

### 3.5.1 Risk from sea level rise (SLR)

The intersection between a projected 1m SLR and the predicted occurrence of turtles in sub-catchments across the study area is illustrated for the Northern long-neck turtle, the Pig-nose turtle, the Gulf-snapping turtle and the Red-faced turtle (Figs. 33a-d, respectively). About 10% of sub-catchments will be affected by a 1m SLR where at least one turtle species is predicted to occur (n=13 species, Kennard 2010). As highlighted by the distribution of the Gulf-snapping turtle (Fig. 33c), some species will not be at risk from SLR because they occur far from the coast. On average about 3 (21%) species of turtle are predicted to occur in sub-catchments affected by a 1m SLR.

Similarly, potential SLR impacts are illustrated for the Barramundi, the Common archer fish, the Golden Goby and the Sooty grunter (Figs. 34a-d, respectively). About 18% of sub-catchments will be affected by a 1m SLR where at least one turtle species is predicted to occur (n=103 species, Kennard 2010). On average about 22 (21%) species of fish are predicted to occur in sub-catchments affected by a 1m SLR.

For waterbirds potential SLR impacts are illustrated for the Magpie goose, the Green pygmy goose, the Great cormorant and the Glossy ibis (Figs. 35a-d, respectively). About 19% of sub-catchments will be affected by a 1m SLR where at least one species of waterbird is predicted to occur (n=106 species, Kennard 2010). In contrast to turtles and fish, on average about 74 (70%) species of waterbird are predicted to occur in sub-catchments affected by a 1m SLR.

Statistical distributions characterising the SLR risk profiles for each taxonomic group are summarised in Appendix A (Table 6e) and illustrated in Figures 36a & b. In contrast to turtles and fish, the waterbird SLR risk profile is highly skewed towards high risk (peaks at 0.85). The combined risk profile therefore has a dangerous positive skew (Fig. 36c). Sensitivity analysis (Fig. 36d) shows that waterbird species contributed 3-4 times more to the combined SLR risk to biodiversity than did species of turtle or fish.

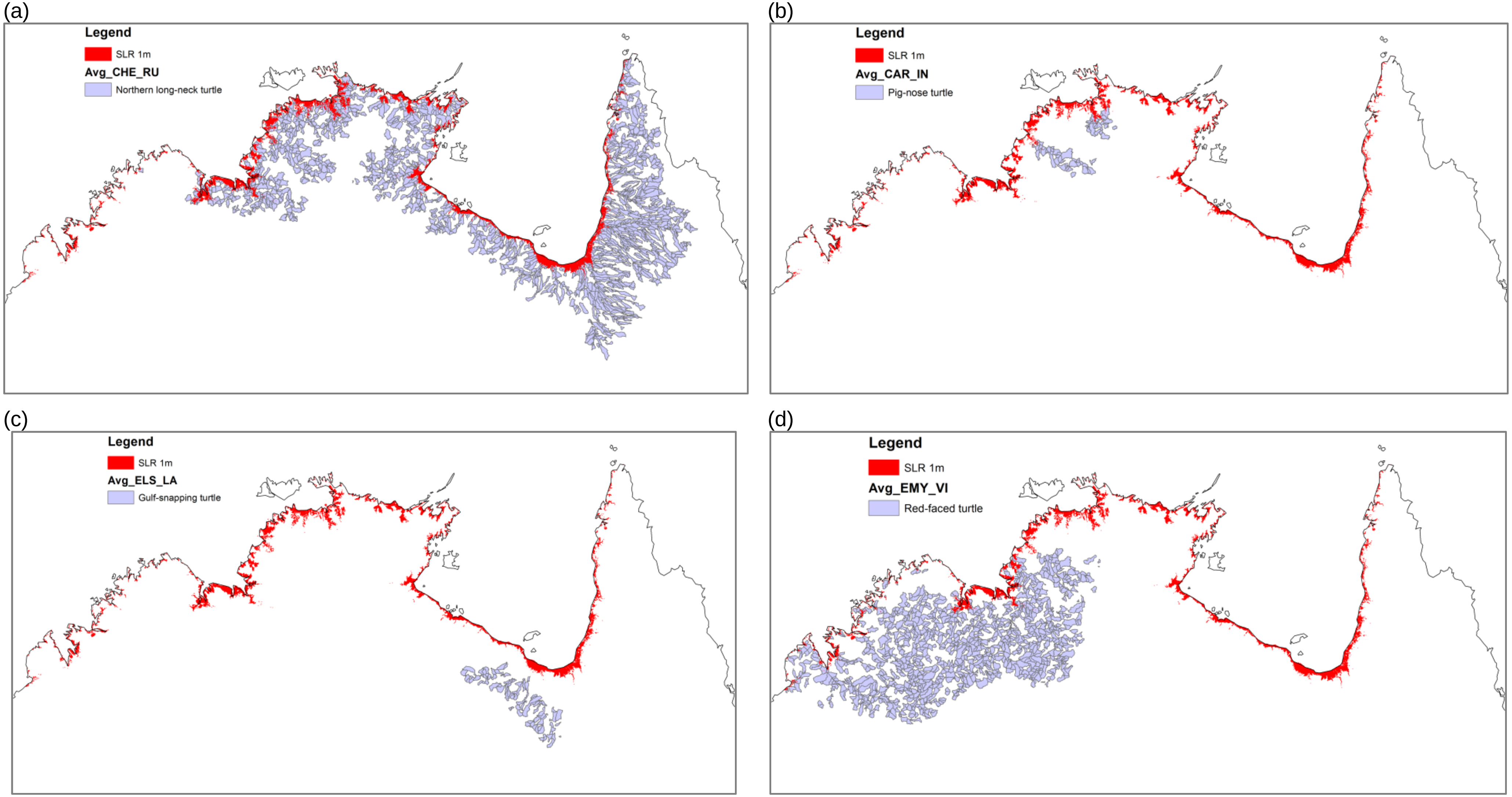



Figure 33a-d. (a) FRESHWATER TURTLE: Predicted distribution (presence only, purple) of (a) Northern long-neck turtle, (b) Pig-nose turtle, (c) Gulf-snapping turtle and (d) Red-faced turtle by sub-catchment unit based on environmental attributes and occurrence records (see Kennard 2010). Distribution models do not extent to the coastal strip. The projected 1m sea level rise is overlaid (red).

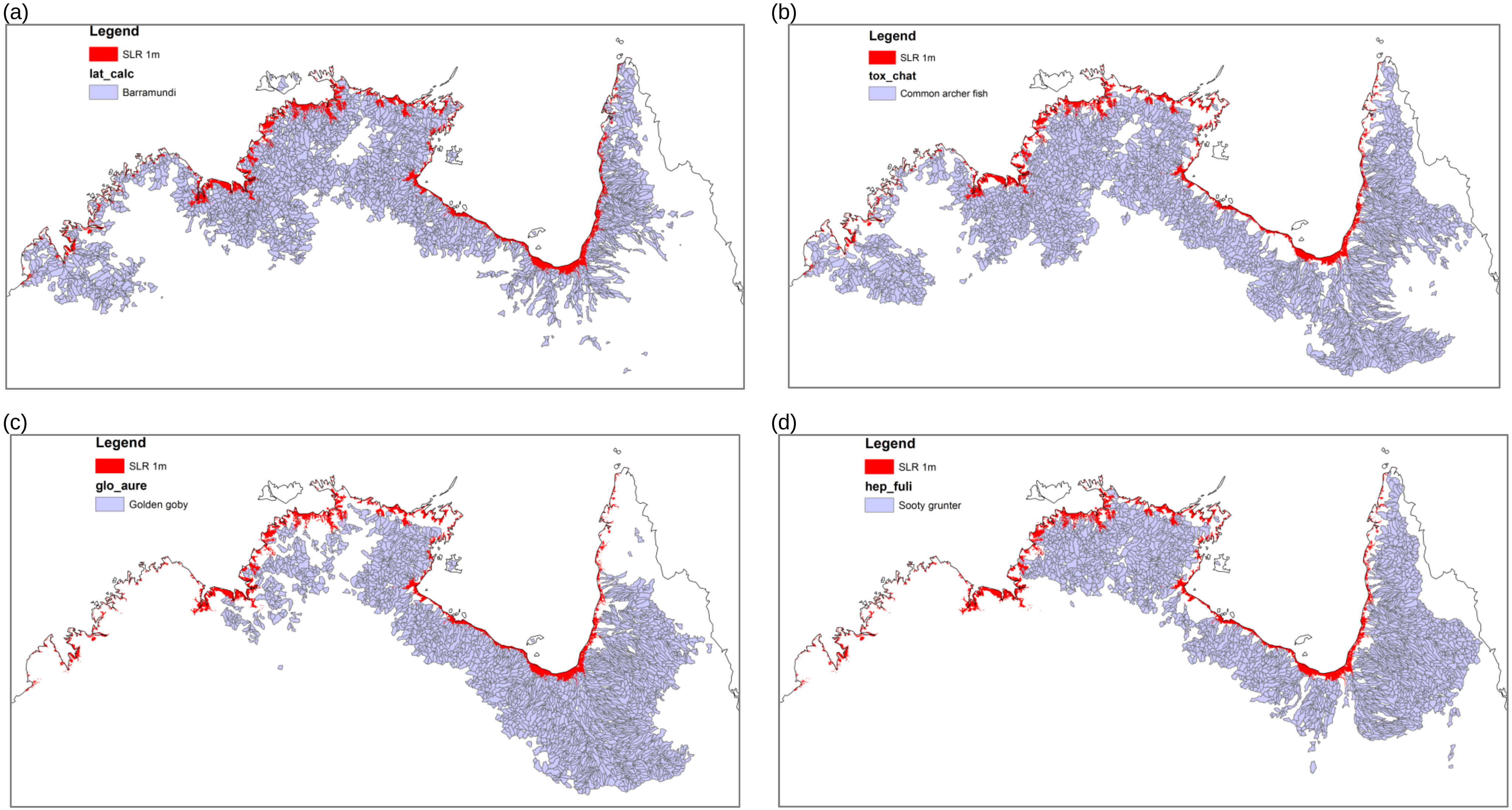



Figure 34a-d. (a) FRESHWATER FISH: Predicted distribution (presence only, purple) of (a) Barramundi, (b) Common archer fish, (c) Golden goby and (d) Sooty grunter by sub-catchment unit based on environmental attributes and occurrence records (see Kennard 2010). Distribution models do not extent to the coastal strip. The projected 1m sea level rise is overlaid (red).

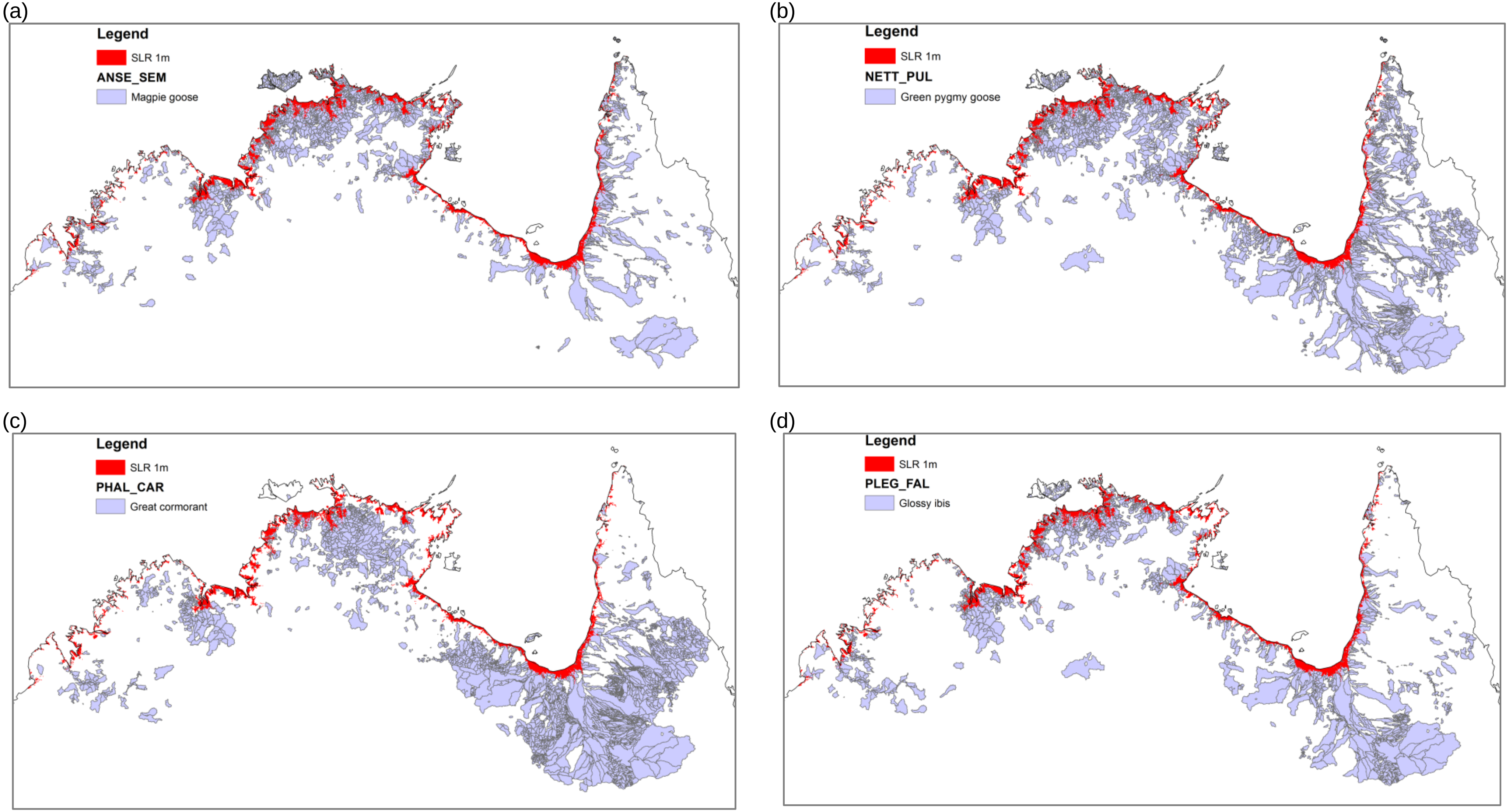



Figure 35a-d. (a) WATERBIRDS: Predicted distribution (presence only, purple) of (a) Magpie goose, (b) Green pygmy goose, (c) Great cormorant and (d) Glossy ibis by sub-catchment unit based on environmental attributes and occurrence records (see Kennard 2010). Distribution models do not extent to the coastal strip. The projected 1m sea level rise is overlaid (red).

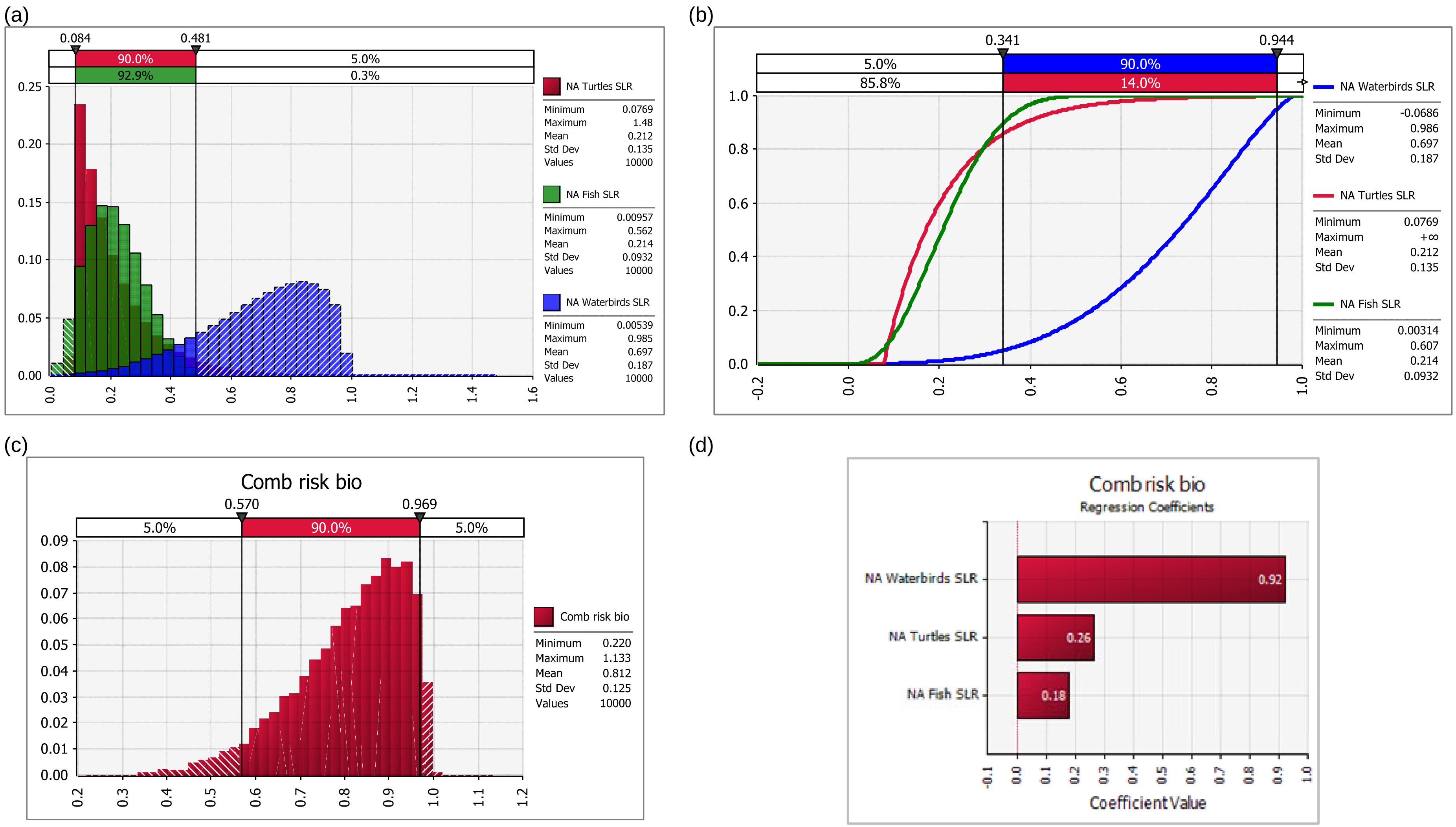



Figure 36a-d. (a) Relative frequency and (b) cumulative probability distributions of the mean proportion in sub-catchments of turtle (brown), fish (green) and bird (blue) species that occur in the northern Australia study area that are likely to be affected by a 1m Sea Level Rise (SLR). The proportions characterise the SLR risk profiles for each taxonomic group. (d) The risk profile for each taxonomic group combined showing the strong skew to high risk. (e) Sensitivity analysis (Tornado graph) showing that waterbirds contributed 3-4 times more to the combined risk from SLR than did turtle and fish, respectively.

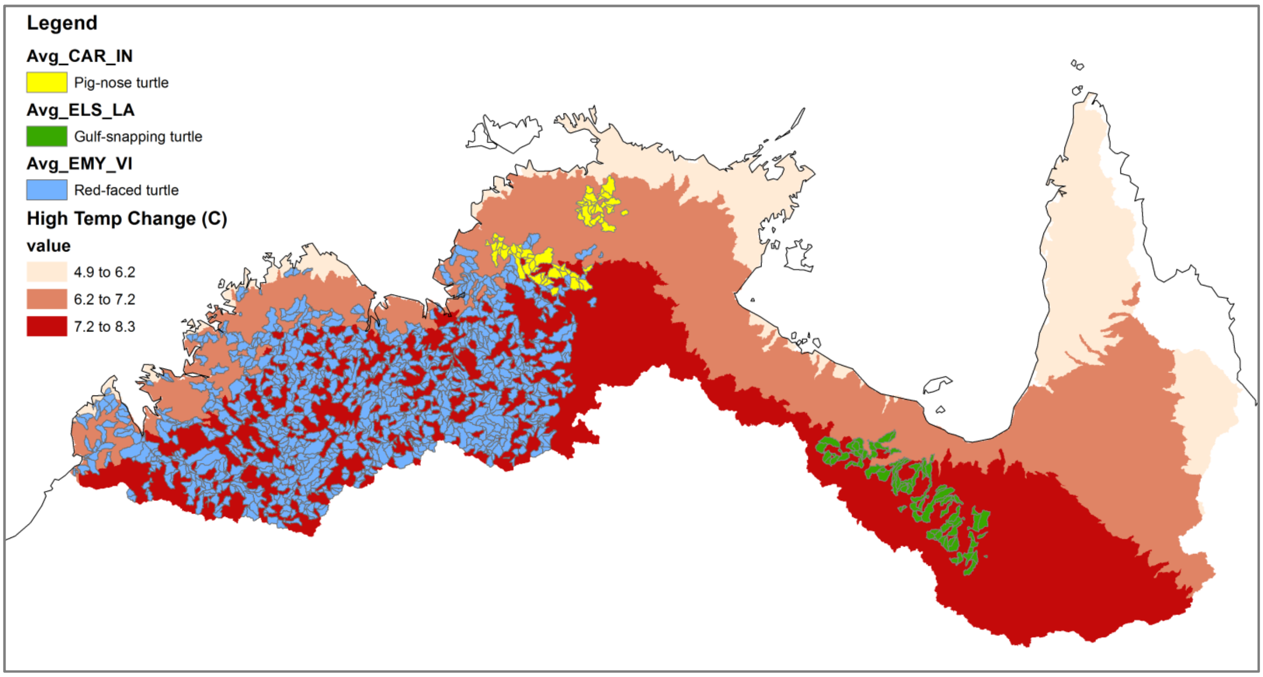
### 3.5.2 Risk from changes in rainfall & ambient temperature

The projected change in ambient temperature ($^0$C/y) across the northern Australia study area in 2100 was simulated for a hotter climate scenario (i.e. the highest temperature range used) in OzClim (CSIRO 2008). Using the GIS method described above for predicting SLR and species overlaps, the co-occurrence of a handful of aquatic species and a projected Hotter Temperature climate change scenario is illustrated for Pig-nose turtle, the Gulf-snapping turtle and the Red-faced turtle (Fig. 37a), and the Kimberley archer fish and the Sooty grunter (Fig. 37b).

The projected change in annual rainfall (mm/y) across the northern Australia study area in 2100 was simulated for a Hotter Wetter and a Hotter Drier climate scenario in OzClim (CSIRO 2008). The predicted co-occurrence of Magpie geese and Green pygmy geese with these two climate change scenarios is illustrated in Figures 38a&b, respectively.

Hence, whilst exposure probabilities can be simply estimated any quantitative risk assessment would be incomplete because there are almost no data on species-specific threshold effects to temperature and rainfall changes. That is, there no available and/or reliable assessment end-points that may eventually influence distribution and abundance patterns, such as reproduction, growth and survival rates. Additionally, for aquatic species, ambient air temperature would likely be a poor correlate of water temperatures. Nevertheless, given that high spatial resolution species occurrence models have already been developed by Kennard (2010) for NWAFA1, and which include climatic and hydrological variable, there is much potential to apply the approach developed by Bond et al. (2011) for the exploration of predicted range shifts of freshwater fish under future climate-change scenarios. This applies to all taxonomic groups, not just fish, and would comprise an exciting future research agenda that should close significant knowledge gaps.

## (a) HOTTER climate in 2100 (Temperature Change $^0$C/y).




## (b) HOTTER climate in 2100 (Temperature Change $^0$C/y).

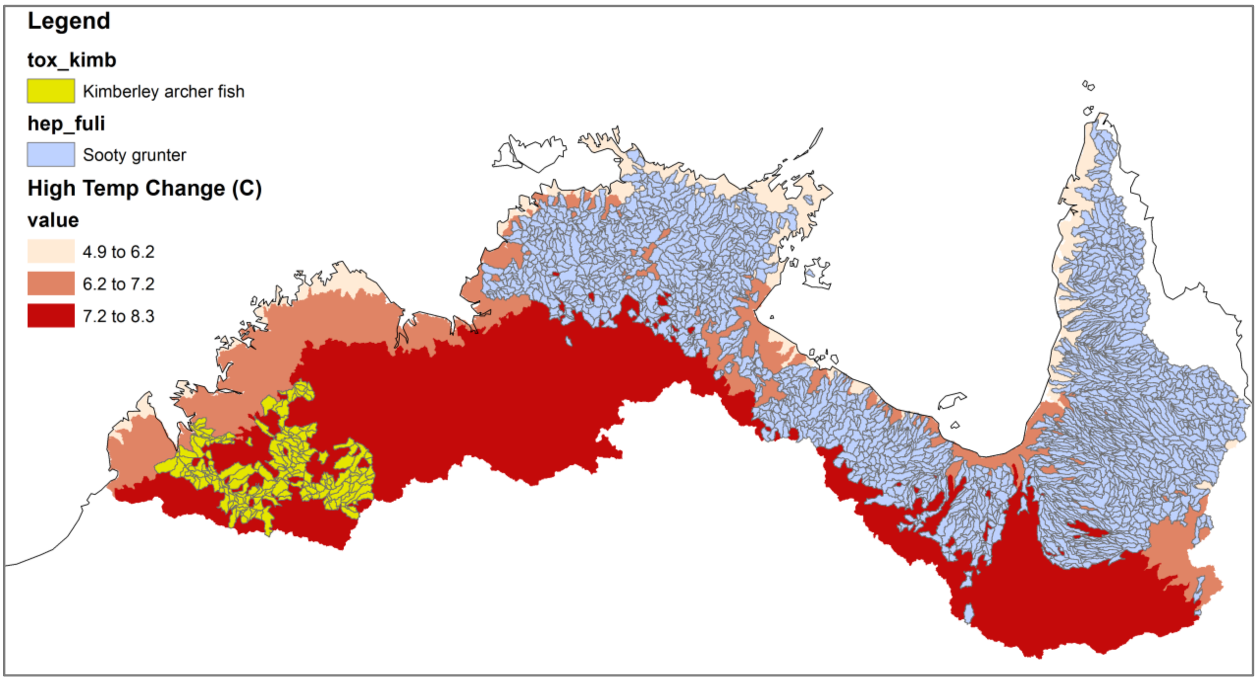
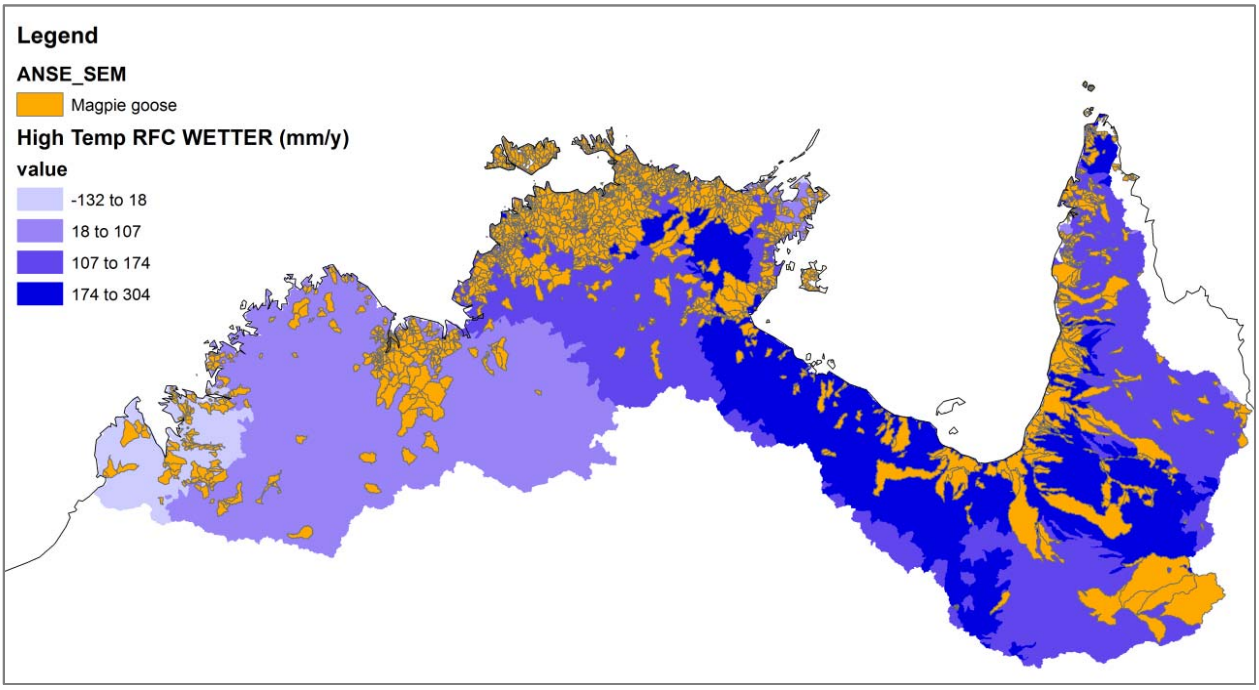



Figure 37a & b. Map of the projected change in annual ambient temperature ($^0$C/y) across the northern Australia study area in 2100. The OzClim (CSIRO 2008) scenario simulation model for a hotter climate was used. The predicted co-occurrence of a handful of aquatic species and projected temperature changes is illustrated. (a) Pig-nose turtle, the Gulf-snapping turtle and the Red-faced turtle. (b) The Kimberley archer fish and the Sooty grunter.

## (a) HOTTER & WETTER climate in 2100 (Rainfall Change mm/y).




## (a) HOTTER & DRIER climate in 2100 (Rainfall Change mm/y).

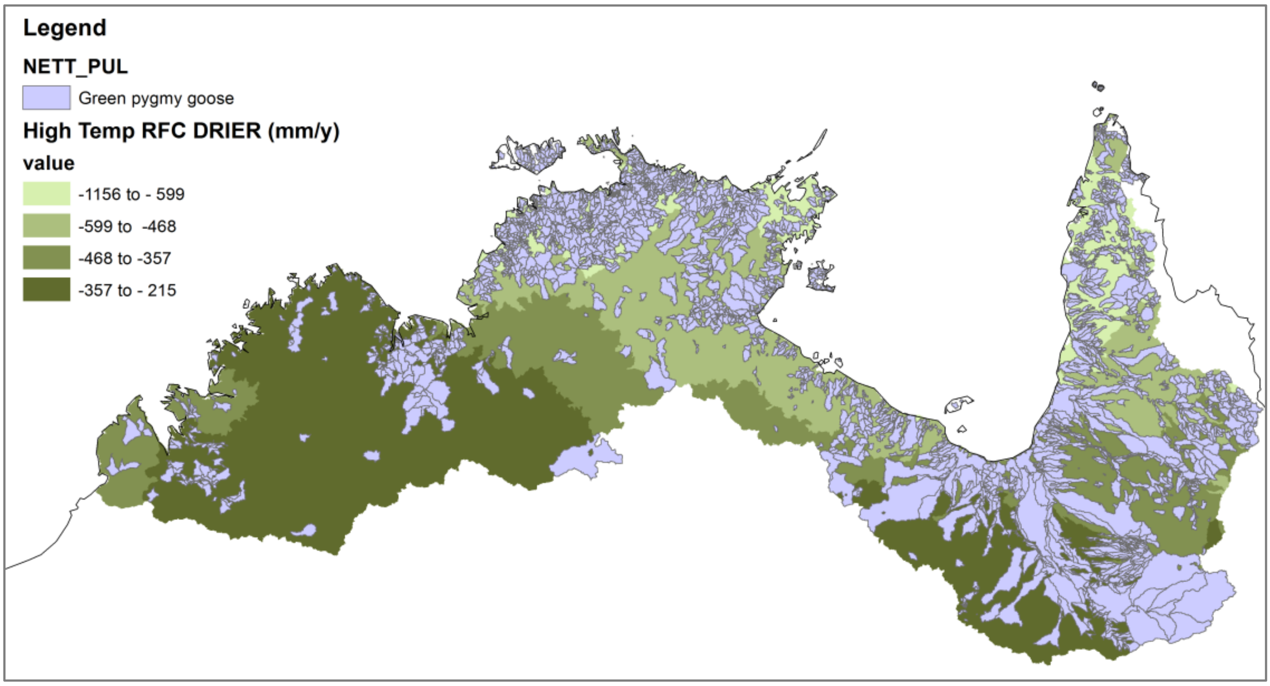



Figure 38a & b Map of the projected change in annual rainfall (mm/y) across the northern Australia study area in 2100. The OzClim (CSIRO 2008) simulation model results for hotter (i.e. high temperature range) and (a) wetter and (b) hotter and drier climate scenarios were used. The predicted co-occurrence of (a) Magpie geese and (b) Green pygmy geese with these two climate change scenarios is illustrated.

## 3.6 Integrating Bayesian Belief Network (BBN)

A Bayesian Belief Network (BBN) was constructed using Netica$^{TM}$ (2010) software to integrate all spatially-explicit risk assessment results of the revised RRM reported here, as suggested by Landis (2009). The pdf profiles for Development and SLR risks to aquatic ecosystem types exhibited complex multi-modal patterns that were sufficiently characterised using statistical functions available in @Risk$^{TM}$ (2010), but could not be incorporated into BBNs derived by Netica$^{TM}$ (2010) because of their limited suite. As flagged in section 2.7 an alternative computational method was developed to derive risk equations to incorporate into the BBN. Linear and polynomial regression analyses were used to predict the probability of risk to aquatic ecosystem types and HCVAE99 assets from associated Development and SLR threats (Table 5). Mean basin values used in analysis are summarised in Appendix B (Table 7). The exposure probability from Development threats was the adjusted RDI derived by combing the CDI and FRDI (see section 2.4.2), and that for a projected 1m SLR the proportion of asset inundated (either km of Riverine, or km$^2$ of Palustrine & Lacustrine, ecosystems). Linear regression equations adequately predicted Development risks to aquatic ecosystems and, that for SLR risks, 3rd order polynomial regression equations (Table 5).

The BBN (Figs. 39 & 40) basically reflects our conceptual model of the risk assessment process across the northern Australia study area, and can also be used at the basin scale by substituting broad-scale mean values with corresponding basin values (i.e. by selecting “Known values” in Netica$^{TM}$ rather “Uncertain” values). The BBN shows all links and interactions between threats, assets and risks assessment endpoints, essential for undertaking “what if” scenario simulations. The BBN can be used also to “hind-cast” effects. For example, by choosing a desired level of risk in one of the assessment endpoint nodes, users can ascertain what threat level is needed in preceding parent nodes in order to achieve the desired state level.

There are three core components to the BBN: (i) Development risks to aquatic ecosystem types (brown nodes); (ii) SLR risk to these same assets (blue nodes); and (iii) both Development and SLR risks to HCVAE99 assets (green nodes). The HCVAE99 assets component in all risk assessments is kept separate from the aquatic ecosystems component because it is assumed that the criteria used in the HCVAE framework to develop the metric had already capture many elements of aquatic ecosystems.

The BBN has two decision nodes for scenario simulation. The first is a “time switch” for SLR risk (grey node, bottom RHS). The 2010 time frame for Development risk is incompatible with the 2100 time frame for a projected 1m Sea level rise risk. Hence, users can choose either 2010 with zero sea level rise, or 2100 when the risk is expected to be measurable. The cascading effect on the combined risk probabilities at different assessment endpoints can be observed (e.g. Development only, SLR only, HCVAE99 only, or any combination of endpoints).

When combing both total Development and total SLR risks (the ultimate assessment endpoint, red node), we assumed that development will remain constant for the next 88 years, which of course is nonsense. Hence, the second decision node (grey node, top LHS) allows users to choose a “percentage increase in development” level, and assumes that this is directly proportional to simultaneous increases in both the CDI and the FRDI. The overall effect on total Development risk is assumed to operate over any time frame since 2010, including up to 2100 and, hence, this decision node can also be considered a “time switch”.

The BBN in Figure 39 shows current (2010) risks to aquatic ecosystem and HCVAE99 assets with the “increases in development” node set to zero and the “SLR time switch” set to 2010 (i.e. zero effect). Results show that, on average across the northern Australia study area, risk from total Development is 48%. When development is increased by 50% then this risk increases by 12% to 60%. Zooming ahead to 2100, SLR risk kicks in at 18% and, if no further development occurs since 2010 (i.e. remains the same at 48%), then the combined risk is 57% (Fig. 40). However, if development increases by 50% then the combined risk is 68% or an increase of 11% (although, as the preceding spatial risk assessments shows, with much variability across the study area).

Netica™ software allows users to also undertake sensitivity analysis on a BBN in order to determine which, of any selected variables, contribute most to any selected assessment endpoint. For example, for the scenario settings in Figure 40, total Development risk contributed 12 times more to combined risk than did SLR risk.

Table 5. Summary of equations used to predict the probability of risk (P) to Riverine (R), Palustrine (P) and Lacustrine (L) aquatic ecosystems, and HCVAE99 assets (H99), from Development (D) and Sea Level Rise (SLR) threats. Mean basin values were used (see Appendix B, Table 6). The exposure probability for Development was the adjusted RDI (see section 2.4.2), and that for SLR the proportion of asset inundated (PI) (via km of Riverine or $km^2$ of Palustrine and Lacustrine ecosystems). All equations are used in the BBN.

| Prediction | Equation | $R^2$ (%) | N | P |
|---|---|---|---|---|
| Development: Riverine | $P_{D(R)} = 0.99\ RDI + 0.01$ | 97 | 53 | P < 0.001 |
| Development: Palustrine | $P_{D(P)} = 1.04\ RDI + 0.005$ | 96 | 53 | P < 0.001 |
| Development: Lacustrine | $P_{D(L)} = 1.02\ RDI + 0.02$ | 75 | 53 | P < 0.001 |
| SLR1: Riverine | $P_{SLR(R)} = 34.0\ PI^3 - 20.8\ PI^2 + 4.0\ PI + 0.012$ | 75 | 53 | P < 0.001 |
| SLR1: Palustrine | $P_{SLR(P)} = 11.2\ PI^3 - 4.4\ PI^2 + 0.5\ PI + 0.003$ | 88 | 53 | P < 0.001 |
| SLR1: Lacustrine | $P_{SLR(L)} = 11.5\ PI^3 - 5.1\ PI^2 + 0.6\ PI + 0.001$ | 71 | 53 | P < 0.001 |

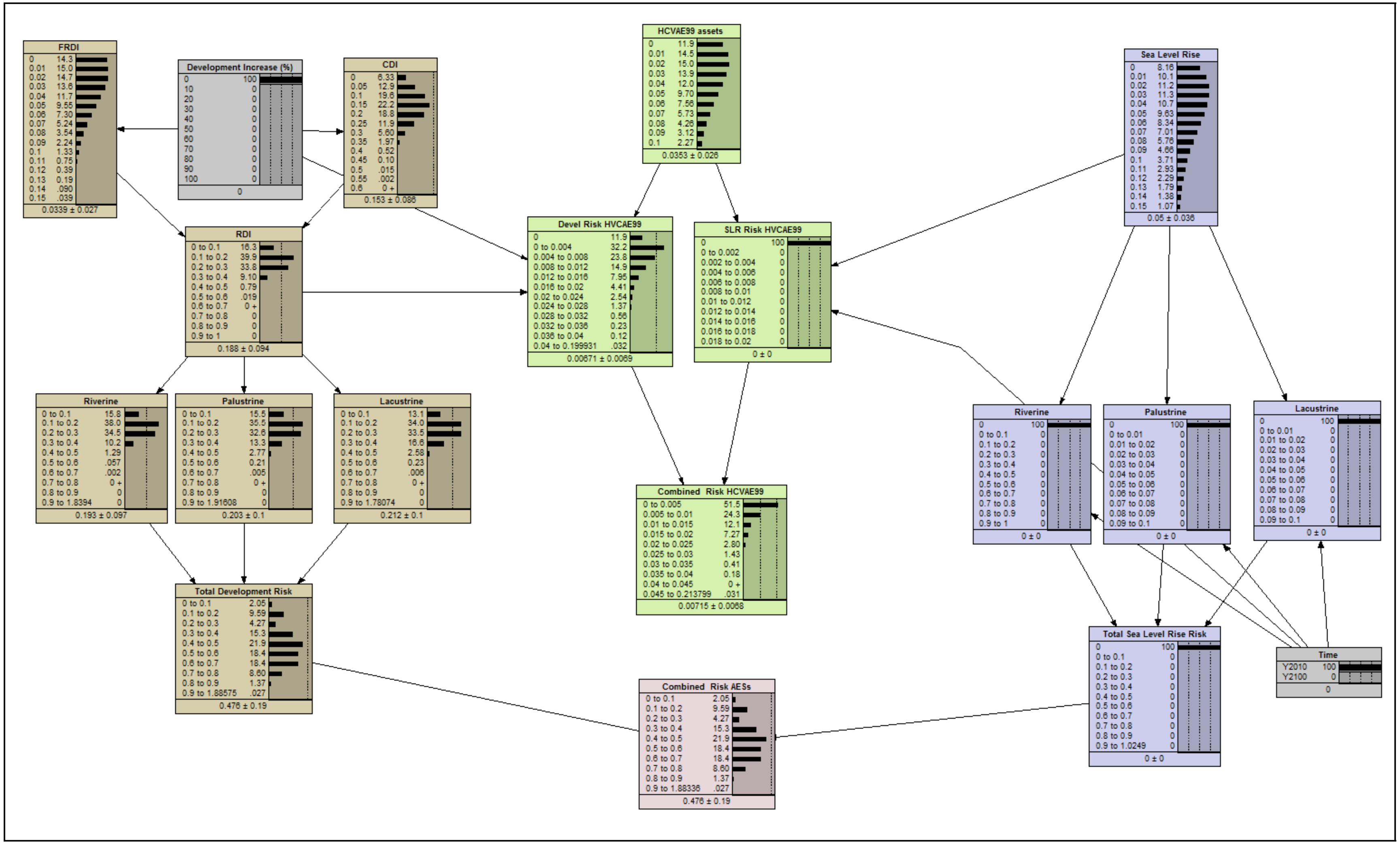



Figure 39. Bayesian Belief Network (BBN) that integrates all outputs from the spatially-explicit risk assessment across the northern Australia study area using the revised RRM (see combined or final assessment endpoint, red node). Risks to aquatic ecosystems from Development and Sea Level Rise (SLR) are the brown and blue nodes, respectively. The green nodes are risks to HCVAE99 assets from both factors. The grey nodes are decision switches for scenario simulation (e.g. % increase in development top LH corner; setting the time frame for SLR risk to manifest in 2100, bottom RH corner). The “increase in development” switch is set to 0% and the SLR “year” switch is set to 2010.

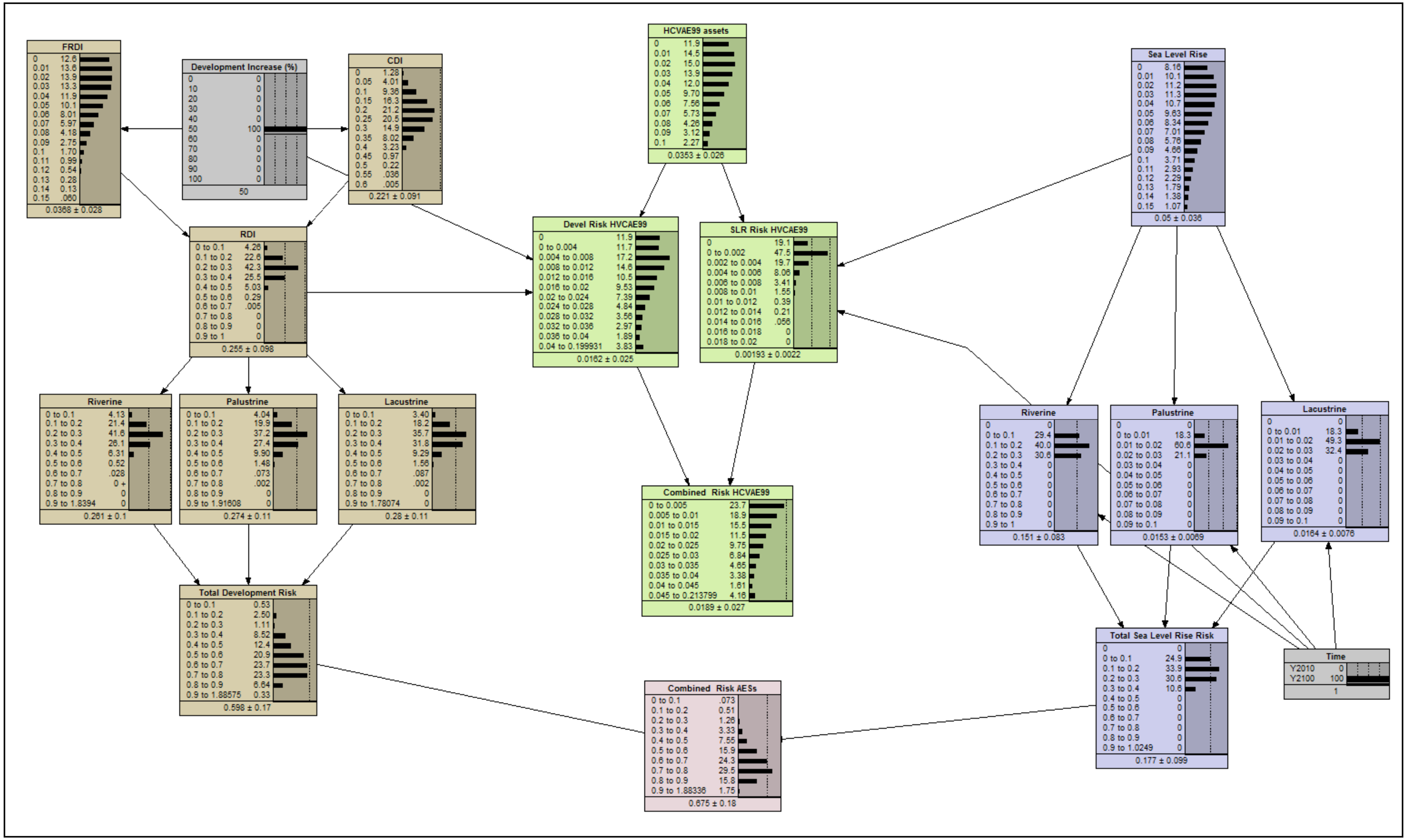



Figure 40. The same BBN as in Figure 40 but with the “increase in development” switch set to 50% and the Sea Level Rise (SLR) “year” switch set to 2100.

# 4. DISCUSSION & RECOMMENDATIONS

The Discussion section specifically relates to results from Activities 3, 4 and 8 of the NAWFA project, with accompanying recommendations to help close identified knowledge gaps.

### Activity 3: Update and revise the spatially-explicit RRM

Despite the number of major water resources projects completed in northern Australia over the last two decades, the first broad-scale "formal" risk assessment of freshwater aquatic habitats from contemporary land use activities (development) and future climate change (sea level rise) threats was undertaken by Bartolo et al. (2012) in 2006, using the spatially-explicit and semi-qualitative Relative Risk Model (RRM) approach developed by Landis and Wiegers (2005, & see Landis 2009) for regional assessments.

The first component of Activity 3 (section 1) relates to updating the RRM using the most recent threats (landuse) and assets (habitat) data, and this is reported in detail in section 1 of this Chapter. However, there are advantages and limitations in the methodology, as summarised by Bartolo in section 1 (Table 5.1). The advantages are considerable given the severe limitations of applying standard "point-source" exposure-effects risk models at regional spatial scales, let alone the general lack of data across remote northern Australia. For example it: provides a robust framework for ecological risk assessment at the regional scale; it enables multiple pressures/threats to be assessed against multiple ecological assets (assessment endpoints); and provides a high level screening tool for decision makers, and graphical outputs/maps of the risk characterisation process.

However, the project team identified several major limitations that required revision to significantly enhance the RRM for use in the current NAWFA project, and additionally to integrate previous NAWFA data and models produced by Kennard (2010) since the TRIAP project was completed. These limitations are (section 1, Table 5.1): ranks and risk scores are relative and so do not provide an estimate of absolute risk; relative ranks from one regional model cannot be compared with relative ranks from another regional model; information critical to the development of a risk score is not readily evident in the output; it only provides an indication of exposure through comparing areal extents of pressures/threats and habitats; and it is difficult to quantify uncertainty around ranks within the model typically requiring a Monte Carlo or similar approach to address. The last limitation is critical as uncertainty and sensitivity analysis are now a major and standard component of any risk assessment (Bayliss et al. 2012, Pollino et al.2007, Burgman 2005, Nayak & Kundu 2001, Moss & Schneider 2000).

The RRM was therefore revised to encompass the higher resolution sub-catchment data used in the previous NAWFA1 project (Kennard 2010), including species biodiversity data, and this comprises the second part of Activity 3 (section 2 of Chapter 4). The revised RRM therefore has significantly greater analytical power (6,393 sub-catchment units cf. 55 basin/catchment units). Additionally, the revised model is now quantitatively based using standard exposure-effect risk probabilities (c.f. ranks), which allows risk profiles of all aquatic assets to be developed and, hence, uncertainty and sensitivity analyses to be undertaken; both essential pre-requisites for addressing Activities 4 and 8. The exposure risk from future SLR in the revised RRM was estimated directly from the areal overlap between the aquatic asset and the 1m contour above ADH, not simply their co-occurrence within a spatial unit, therefore reducing one source of uncertainty associated with using ranks.

Regardless of the above analytical enhancements, however, whether or not the revised quantitative RRM performs better than the previous semi-qualitative RMM depends entirely on purpose and utility (see Hilborn & Mangel 1997 for any model). For example, whilst both RRM approaches are spatially-explicit and generally address the same Development and SLR threats, their assessment pathways and endpoints are sufficiently different and complex to make meaningful comparison dubious except at a high level. Comprehensive conceptual models of the risk pathways to assessment and measurement endpoints were developed *a priori* for both RRM modelling approaches (see Fig. 2.5 in section 1 & Fig. 5 in section 2), and show clearly that the revised model cannot supersede the original model. For example, the RRM of Bartolo et al. (2012) assesses risk to five broad yet easily recognisable aquatic habitat classes (Rivers & streams; Wetlands, floodplains & lakes; Springs & waterholes; Riparian vegetation; Mangroves & estuaries) from 14 classes of identifiable landuse and/or development threats, and a 1m SLR threat. The easy identification of assets and threats is likely an advantage when communicating risk results to end-users and stakeholders. In contrast, the revised RRM approach used here assesses risk to three high level aquatic asset types (Riverine, Palustrine & Lacustrine ecosystems), and a composite HCVAE metric (HCVAE99), from two high level surrogates of landuse and development pressures (i.e. the CDI & FRDI; Stein et al. 2002). Integrating NAWFA1 data into the current RRM is therefore impossible without accompanying complex analysis describing the relationship between standard aquatic habitat types and the Hydrosystem classification scheme developed by Aurich (2010). The RRM used in section 1 included the RDI as an additional threat layer, which was also used in NAWFA1 by Kennard (2010). However, the RDI is the mean of the CDI and FRDI (Stein et al. 2002), and the same the same landuse variables are already captured in the RDI via the CDI. Hence, it is effectively a redundant variable in that particular analysis. Given the above, and the fact that they have different strengths and limitations, it was therefore decided to run with both models in a complementary approach.

In summary, a comparison of results for three high level risk assessment endpoints at both basin and sub-catchment scales produced similar outcomes, supporting the two-RRM approach. Bayliss et al. (2008) compared RRM results with more detailed quantitative risks assessments undertaken in sub-catchments of the Daly River basin, and concluded the same.

### Activity 4: Incorporate climate change risk factors (SLR) in the RRM and undertake an assessment to help differentiate climate change risks from development risks, and examine potential interactions between them with respect to cumulative risks.

### Activity 8: Highlight areas where development and predicted climate change will compound degradation.

The results of these two activities are discussed in combination, reflecting the assessment process adopted at all levels: Development and Sea Level Rise (SLR) risks were first assessed independently because they operate at two different time scales (2010 vs. 2100), and then in combination. The assets and threats were first characterised to develop risk profiles, and individual and combined risk factors were then mapped across the entire study area at very high resolution using sub-catchment as mapping units (mean area of $200km^2$, Kennard 2010).

Development, SLR and Combined risks of 53 basins were compared also using mean sub-catchment values. The 15 basins selected by Sate and Territory jurisdictions for focus are highlighted throughout the report, as all basins are assessed at the same high level of detail. Detailed basin-level results, however, are only reported for the Norman River, South Alligator River and Finniss River basin basins, exemplifying the potential of the data for detailed exploratory analysis.

All quantitative risk assessments were accompanied by robust uncertainty and sensitivity analyses to account for inherent uncertainty in data and risk models, and are essential pre-requisites in differentiating potential climate change risk from Development risk because of the interaction between the two risk factors. However, although the quantitative risk model used here accounts for interactions, the underlying model assumption is by necessity still additive given current lack of knowledge on possible synergistic or multiplicative effects. The cumulative effects of both risk factors, as assessed by their combined risk probability, should therefore be used as a starting point only and treated with a degree of caution.

Despite the caveat, however, there may be a diabolically logical argument in favour of using the combined risk probabilities anyway, irrespective of lack of knowledge on potential synergistic effects. Aquatic assets damaged by Development risks beyond repair cannot be damaged by future SLR risks and, similarly, assets damaged by SLR risk cannot be damaged by future Development risks. Given the very different natures of both risk factors, and the fact that areas susceptible to saltwater inundation are generally unfavourable areas for water resource development, a more profitable strategy may be to manage both risks independently rather than to be concerned about what they may do in combination. Needless to say this argument would not apply to climate risks that result from changes in rainfall and stream flow, which are addressed in Chapter 3 using the approach adopted by the NASY project (CSIRO 2009).

The combined risk analysis is an attempt also to address Activity 8. However, without argument, results need to be treated with caution because their exposure and effects manifest at different time scales. The underlying and false assumption on combining both risk probabilities is that that current (2010) Development risk will remain constant for 89 years, which is of course nonsense. Nevertheless, the combined risk maps and profiles represent a “first pass” attempt to highlight areas where the two risk factors may compound degradation to freshwater aquatic assets across the NAWFA study area.

*Result summary*

The overall risk to aquatic ecosystems from Development in 2010 is about five times greater than that from a projected 1m SLR in 2100 (0.39 cf. 0.08, respectively), despite the large variation between basins (0 – 0.93), and this is unsurprising given the extensive and diffuse nature of development threats compared to SLR threats restricted to a relatively narrow margin around the coastline. The overall combined risk is estimated at 0.45 (45%). Basins with aquatic ecosystems most at risk from current Development risks comprised clusters in the southern GoC (Qld) and the Adelaide River basin close to Darwin (NT). In contrast, basins at least risk from current Development comprise clusters in remote Arnhem Land (NT), the South and East Alligator River basins in Kakadu National Park, and the Moyle River basin far from anywhere. The basin most at risk from SLR is Mornington Inlet, being a small low-lying coastal catchment. The Adelaide River basin had the greatest Development risk to HCVAE99 assets, followed by the adjacent Mary River basin (0.06 & 0.03, respectively). The Mornington Inlet basin had the highest SLR to HCVAE99 assets (0.002 0r 0.2%), although these values are too small for meaningful comparisons.

The South Alligator River (SAR) and Norman River basins were chosen for more detailed fine-scale comparison of risks because of their contrasting land uses, reflecting a high value conservation area (Kakadu National Park) and an area encompassing intensive land use and associated catchment disturbance, respectively. Aquatic ecosystems in the Norman River basin are 19 times more at risk from development than those in the SAR basin (0.50 cf. 0.03) and, in contrast, aquatic ecosystems in the SAR basin are 3.7 times more at risk from SLR. The risk to HCVAE99 assets from Development in the Norman River basin is twice that of the South Alligator River basin (mean 0.013 cf. 0.008). In contrast, SLR risk is 13 times greater in the South Alligator River basin than the Norman River basin (mean 0.026 cf. 0.002).

The Finniss River basin (NT) was chosen as a detailed case study area to compare RRM methodologies. Additionally, the basin is at risk from increasing development pressures due to an expanding urban population in nearby Darwin (& ranked most at risk in section 1), and the detailed analysis reported here will comprise much needed baseline given that there are no previous assessments. Aquatic ecosystems were at similarly high risk levels from Development and SLR (0.38 & 0.36, respectively). The combined risk is therefore high (0.60), reflecting significant catchment disturbances associated with aquatic ecosystems susceptible to SLR. The risks to HCVAE99 assets from Development and SLR were very small (0.01 & 0.0003, respectively).

An assessment of SLR threats to biodiversity (via their habitats) was undertaken using turtles, fish and waterbirds as surrogates for total biodiversity. The level of risk in coastal sub-catchments was estimated from the intersection between a projected 1m SLR and predicted species occurrences using the presence-only Habitat Suitability Models developed by Kennard (2010). About 10% of sub-catchments where at least one species of turtle is predicted to occur will be affected by a 1m SLR, and that for fish and waterbirds 18%. The mean risk to waterbird species was about three times greater than that for turtles and fish (0.70 cf. 0.21 for both).

A similar risk assessment for the effects of increased environmental temperature due to climate change was not undertaken given the lack of comprehensive (or any) data on species-specific threshold effects of increased temperature on population-level assessment endpoints such as growth, reproduction and survival. Hence, predictive models need to be developed to explore potential range shifts of freshwater species under future climate-change scenarios. However, a framework was developed to predict potential exposures of changes in ambient temperature on species in the NAWFA study area, under different climate change scenarios generated by OzClim (CSIRO 2008). Nevertheless, given that high spatial resolution species occurrence models have already been developed by Kennard (2010) for NWAFA1, and which include climatic and hydrological variable, there is much potential to apply the approach developed by Bond et al. (2011) for the exploration of predicted range shifts of freshwater fish under future climate-change scenarios. This applies to all taxonomic groups, not just fish, and would comprise an exciting future research agenda that should close significant knowledge gaps.

In summary, the overall results reported here are consistent with our current knowledge of risks to basins in northern Australia, as determined by the findings of all previous water resource assessment projects (e.g. section 2 of this Chapter, Kennard 2010, Kennard et al. 2010b, Pusey & Kennard 2010, NALWTF 2009, CSIRO 2009, Bartolo et al. 2008, van Dam et al. 2008);

basically there were no surprises. Additionally, our quantitative risk assessment results are reported within a consistent, transparent and robust framework.

Of particular relevant to our study are the general and specific outcomes of 'The Northern Australia Land and Water Science Review (NALWTF 2009)' with respect to Terms of Reference 3 – "*Identify the potential impact of such (identified potential – ToR 2) development opportunities on the natural environment and other users and the broader community.*"

In general, the Review highlighted the fact that cultural life and economic activities associated with non-consumptive water use (e.g. Indigenous cultural use, tourism, coastal fisheries) in northern Australia are inextricably linked to the region's high natural values, which in turn emanate from the intact landscapes and relatively undisturbed flows of the north's waterways (Pusey & Kennard 2010). The Review emphasises also that Development can directly reduce these values through disturbances to catchments and natural flow regimes (e.g. through depleting water, reducing water quality and/or by changing the natural flow of water in the landscape), all of which impact on aquatic, marine and terrestrial environments (e.g. see Kennard et al. 2010). Our spatially-explicit risk assessment results of both Development and sea level risk risks in northern Australia, and both basin and sub-catchment scale, is therefore an important contribution towards identifying and quantifying risks to these unique natural values in a robust and transparent manner, and is an important baseline to assess future change.

Specifically, the review of Aquatic Ecosystems in northern Australia by Pusey and Kennard (2010), where they identify the critical links between aquatic ecology and development of northern Australia is highly relevant to our risk assessment. They emphasise that the movement of water and associated nutrients, carbon and energy between different hydrosystem components of aquatic ecosystems, and the maintenance of connectivity, is vital for natural ecosystem function. Furthermore Pusey and Kennard (2010) argue that extensive Development in northern Australia, and global climate change impacts, will severe these ecological links which will likely lead to a loss of ecological integrity and value.

### The next step in the risk assessment process – integrated assessments

Managing any complex socio-ecological system is a very difficult task and cannot be underestimated (Gunderson et al. 2008; de la Mare 2006, Stepp et al. 2003, Costanza et al. 1993), and this caveat applies to river basins across the NAWFA study area. Natural resource managers are required to achieve high level goals in the face of uncertainty and limited resources. Good environmental outcomes are expected at least cost and yet, at the same time, there is an obligation to balance stakeholder interests and needs. Hence, there are complex and often conflicting objectives involved in NRM, particularly when we consider cultural, social, political and economic objectives. An additional challenge is that more often than not we have incomplete and variable information, thus explaining the increasing adoption of risk assessment approaches as exemplified by this project.

Few would disagree that Adaptive management (AM) is the solution to NRM, as the approach helps us understand 'where we are' and 'where we want to be' with respect to the system we want to manage. Unfortunately, however, it does not come with "off-the-shelf" guidelines about how to make the approach operational. Management Strategy Evaluation (MSE) via computer simulation is an operational version of AM and comes with objectives, targets and performance indicators, and which are all linked to decisions made by managers. The MSE simulation approach was originally designed to assess alternative fisheries management regimes in the face of high levels of uncertainty (de la Mare 2005, Punt 2001, Sainsbury 2000, Smith 1994), but is now increasingly used in other domains such as the coastal (McDonald 2006) and terrestrial (Milner-Gulland et al. 2010) zones. Additionally, participatory modelling methods are now being used to engage with stakeholders at the outset, in order to integrate socio-economic and cultural knowledge, and to develop the specifications of the computer simulation model ensuring ownership and control (e.g. Dutra et al. 2011, Pantus et al. 2011, Woodward et al. 2011, Chan et al. 2010b, Montes de Oca Munguia et al. 2009). Nonetheless, the MSE approach is not without criticism. Whilst Rochet and Rice (2009) suggested that a simulation-based MSE approach is, without question, a significant step forward in fisheries management because it provides a tool to help make the precautionary approach operational, it can sometimes be ignorance disguised as mathematics.

There has been considerable investment in developing highly predictive biophysical models to help design management actions at any given time, and undertaking comprehensive and highly sophisticated risk assessments, and these need to be the best available. Whilst MSE is complementary to these two approaches, its main purpose is to help us decide whether or not we have an AM system that can provide us with enough information to track that our actions are having the desired effect. If so then the AM system has the ability to implement a course correction in order to reach our objective.

A Bayesian Belief Network (BBN) was constructed to integrate and communicate all spatial risk assessment results using the revised RRM, and can be used at any reporting scale (e.g. across northern Australia or by basin and sub-catchment). Users can choose one of two reference time frames, 2010 (recent) or 2100 (future), and a projected percentage increases in Development. The BBN was designed to undertake "what if" scenario simulations and, hence, may be a useful Decision Support Tool for catchment managers (see Barton et al. 2008). The essential "next step" in the risk assessment process is to incorporate these outputs into an overall integrative assessment of all NAWFA outputs, particularly the socio-economic and flows threshold components, and then into an MSE framework. This may lead to research being applied rather than shelved. However, the last step in the "path to impact" approach to risk assessment is beyond the current resources of this project and, hence, is a major recommendation (see below). These ideas are discussed in the Integration Chapter of the project, which also contains a comprehensive literature review of the MSE approach.

## Recommendations

Key parts of the risk assessment processes adopted here remain unfinished due lack of resourcing and the very short time frame for completing the project. These comprise technical issues associated with methods development, and major issues of application of risk assessment results.

*Technical*.

1. The general recommendations suggested by Bartolo in section 1 also apply to the revised RRM, in particular the application of weights (& hence filters) to asset and threat data. Both approaches assume that these are equally weighted within and between basins, as measured by either their spatial overlap or their co-occurrence in an assessment unit, which of course may not be true. This is an emerging area in risk assessment (Burgman 2005) and requires dedicated research effort and participation by stakeholders.

2. All risk assessments need to be underpinned by decent conceptual models of how the system we wish to mange works (Burgman 2005). Another emerging and key area of risk analysis that was not addressed in this project due to time constraints, and related to the derivation of weights, is an objective assessment of elicitation methodologies used to obtain subjective "expert opinion" used to construct conceptual models that are often incorporated into BBNs and advocated as a Decision Support Tool. This is a significant knowledge "social" knowledge that needs to be addressed.
3. Further work is required to integrate both RRM approaches used here, particularly the different classification systems used to characterise threats and assets (e.g. habitats vs. hydrosystems, landuse vs. the RDI), and to develop analytical methods to analyse uncertainties associated with semi-qualitative relative risk ranks

*Application*

4. A separate follow-up project is required to develop, and implement, effective methods to communicate complex risk assessment outputs to stakeholder and end-users, in particular the critical role that uncertainty analysis plays in determining confidence in results and therefore subsequent use in the decision making process.
5. The revised RRM model should now be applied the NE Queensland basins in the NAWFA study area.
6. The risk analysis of a mean 1m SLR for aquatic assets, including biodiversity surrogates, should be extended to incorporate the effects of predicted changes in extreme weather events, such as increases cyclone intensity and associated storms surges and high tides.
7. Assessments are required on the potential impact of Development on biodiversity assets (only SLR risk was addressed here).
8. Comprehensive modelling work on the impact of temperature increases due to climate is required in the NAWFA study area. There is currently much potential to apply the approach developed by Bond et al. (2011) for freshwater fish in Victoria to the exploration of predicted range shifts of tropical freshwater fish under future climate-change scenarios.
9. The risk assessment process commenced here must now shift its focus from characterising risk to assessing development scenarios in northern Australia. Hence, we recommend strongly that the results reported here be incorporated into a Management Strategy Evaluation (MSE) framework, which would facilitate integrated assessments using all other NAWFA research outputs, particularly the socio-economic and ecological flow-threshold components. Needless to say, this should be a participatory process with all NAWFA stakeholders from the outset, and which would require an appropriate level of investment. These ideas are explored further in the integration Chapter of this report.

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# APPENDIX A

Table 6a-e (Appendix A). Statistical distribution functions.

Summary of the probability density functions (pdfs) used to characterise aquatic ecosystem assets, threats and risk for: (a) the Northern Australia study area across basins (n=6,393 sub-catchment units); (b) basin means (n=53 AWRC basins/catchments); (c) the South Alligator River and Norman River basins with contrasting land use; (d) the Finniss River basin; and (e) Biodiversity risk profiles for turtles, fish and waterbirds to a projected 1m sea level rise in 2100.

Table 6a.

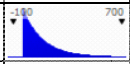
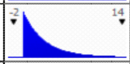
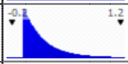
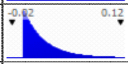
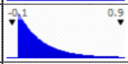
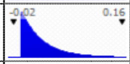
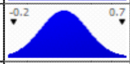
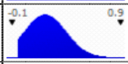
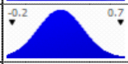
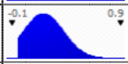
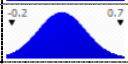
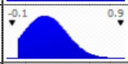
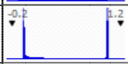
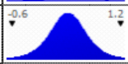
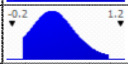
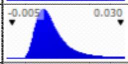
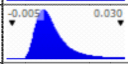
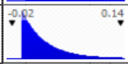
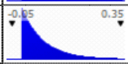
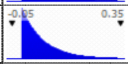
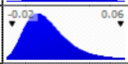
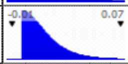
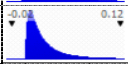
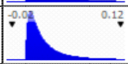
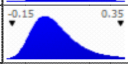
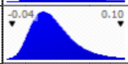
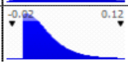
| (a) Northern Australia | Attribute | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|
| NAWFA region | Riverine ecosystem (km) |  | RiskExpon(133.91,RiskShift(-0.020947),RiskName("NA All Riverine"),RiskLibrary(145,"Z67M36R8","RiskLibraryLocal")) | 0.0 | 134 | +∞ |
| NAWFA region | Palustrine ecosystem ($km^2$) |  | RiskExpon(2.8251,RiskShift(-0.0004419),RiskName("NA All Palustrine"),RiskLibrary(146,"V71Z15M5","RiskLibraryLocal")) | 0.0 | 2.825 | +∞ |
| NAWFA region | Lacustrine ecosystem ($km^2$) |  | RiskExpon(0.23062,RiskShift(-0.0000360731),RiskName("NA All Lacustrine"),RiskLibrary(147,"GT4IRFHJ","RiskLibraryLocal")) | 0.0 | 0.231 | +∞ |
| NAWFA region | HCVAE99 (rescaled 1.0) |  | RiskExpon(0.024114,RiskShift(-0.00000377188),RiskName("NA All HCVAE99 rescaled 1.0"),RiskLibrary(156,"19YGLYEM","RiskLibraryLocal")) | 0.0 | 0.024 | +∞ |
| NAWFA region | Catchment Disturbance Inedex (CDI) rescaled to 1.0 across region |  | RiskExpon(0.19238,RiskShift(-0.0000300922),RiskName("NA CDI rescaled to 1.0"),RiskLibrary(127,"DG14RSTM","RiskLibraryLocal")) | 0.0 | 0.192 | +∞ |
| NAWFA region | Flow Regime Disturbance Index (FRDI) |  | RiskExpon(0.031643,RiskShift(-0.00000494958),RiskName("NA FRDI"),RiskLibrary(128,"DXNILR3E","RiskLibraryLocal")) | 0.0 | 0.032 | +∞ |
| NAWFA region | Development Risk Riverine |  | RiskNormal(0.22517,0.17477,RiskName("NA DEV risk River"),RiskLibrary(121,"XL5MRRN9","RiskLibraryLocal")) | -∞ | 0.225 | +∞ |
| NAWFA region | Development Risk Riverine TRUNC |  | RiskNormal(0.22517,0.17477,RiskTruncate(0,1),RiskName("NA DEV risk River TRUNC"),RiskLibrary(124,"DNQYX458","RiskLibraryLocal")) | 0.0 | 0.259 | 1 |
| NAWFA region | Development Risk Palustrine |  | RiskNormal(0.21022,0.16949,RiskName("NA DEV risk Palus"),RiskLibrary(122,"W2DE2HYG","RiskLibraryLocal")) | -∞ | 0.210 | +∞ |
| NAWFA region | Development Risk Palustrine TRUNC |  | RiskNormal(0.21022,0.16949,RiskTruncate(0,1),RiskName("NA DEV risk Palus TRUNC"),RiskLibrary(125,"8KAZICWF","RiskLibraryLocal")) | 0.0 | 0.245 | 1 |
| NAWFA region | Development Risk Lacustrine |  | RiskNormal(0.22205,0.1787,RiskName("NA DEV risk Lacus"),RiskLibrary(123,"Q1JSGRXE","RiskLibraryLocal")) | -∞ | 0.222 | +∞ |
| NAWFA region | Development Risk Lacustrine TRUNC |  | RiskNormal(0.22205,0.1787,RiskTruncate(0,1),RiskName("NA DEV risk Lacus TRUNC"),RiskLibrary(126,"4TXTNV1","RiskLibraryLocal")) | 0.0 | 0.259 | 1 |
| NAWFA region | Total Development Risk (w zeros) 1 |  | RiskBetaGeneral(0.27748,0.71034,0,1,RiskName("NA Dev Total (w zeros)"),RiskLibrary(158,"6TUMWECD","RiskLibraryLocal")) | 0.0 | 0.281 | 1 |
| NAWFA region | Total Development Risk (w zeros) 1 TRUNC |  | RiskBetaGeneral(0.27748,0.71034,0,1,RiskTruncate(0,1),RiskName("NA Tot Dev risks (w zeros) TRUNC"),RiskLibrary(161,"NU4WRLSL","RiskLibraryLocal")) | 0.0 | 0.281 | 1 |
| NAWFA region | Total Development Risk (w zeros) 2 |  | RiskLogistic(0.33418,0.17314,RiskName("NA Tot Dev risk (with zeros) 2"),RiskLibrary(163,"XFHAG16J","RiskLibraryLocal")) | -∞ | 0.334 | +∞ |
| NAWFA region | Total Development Risk (w zeros) 2 TRUNC |  | RiskLogistic(0.33418,0.17314,RiskTruncate(0,1),RiskName("NA TOT DEV TRUNC"),RiskLibrary(167,"FM9R9FX6","RiskLibraryLocal")) | 0.0 | 0.391 | 1 |
| NAWFA region | Total Development Risk to HCVAE99 |  | RiskLoglogistic(0,0.0073055,3,RiskShift(-0.00000114273),RiskName("NA DEV HCVAE99"),RiskLibrary(137,"ZE8BEYRB","RiskLibraryLocal")) | 0.0 | 0.009 | +∞ |
| NAWFA region | Total Development Risk to HCVAE99 TRUNC |  | RiskLoglogistic(0,0.0073055,3,RiskShift(-0.00000114273),RiskTruncate(0,1),RiskName("NA DEV HCVAE99 TRUNC")) | -∞ | 0.009 | +∞ |
| NAWFA region | SLR1m to sub-catchments |  | RiskExpon(0.030699,RiskShift(-0.00000480192),RiskName("NA All SLR1 to cpus"),RiskLibrary(157,"HKQF7CUN","RiskLibraryLocal")) | 0.0 | 0.031 | +∞ |
| NAWFA region | SLR1m Risk Riverine |  | RiskExpon(0.071897,RiskShift(-0.0000118291),RiskName("NA SLR River risk"),RiskLibrary(72,"CHWM8VTT","RiskLibraryLocal")) | 0.0 | 0.072 | +∞ |
| NAWFA region | SLR1m Risk Riverine TRUNC |  | RiskExpon(0.071897,RiskShift(-0.0000118291),RiskTruncate(0,1),RiskName("NA SLR River Risk TRUNC"),RiskLibrary(84,"ZZU5TJIX","RiskLibraryLocal")) | -∞ | 0.072 | +∞ |
| NAWFA region | SLR1m Risk Palustrine |  | RiskExtvalue(0.00072081,0.011733,RiskName("NA SLR Palus risk"),RiskLibrary(73,"2WQ3A65K","RiskLibraryLocal")) | -∞ | 0.007 | +∞ |
| NAWFA region | SLR1m Risk Palustrine TRUNC |  | RiskExtvalue(0.00072081,0.011733,RiskTruncate(0,1),RiskName("NA SLR Palus Risk TRUNC"),RiskLibrary(85,"DQD3EBAQ","RiskLibraryLocal")) | 0.0 | 0.015 | 1 |
| NAWFA region | SLR1m Risk Lacustrine |  | RiskInvgauss(0.025,0.025,RiskName("NA SLR Lacus risk"),RiskLibrary(75,"SRJPAYE7","RiskLibraryLocal")) | 0.0 | 0.025 | +∞ |
| NAWFA region | SLR1m Risk Lacustrine TRUNC |  | RiskInvgauss(0.025,0.025,RiskTruncate(0,1),RiskName("NA SLR Lacus risk TRUNC")) | 0.0 | 0.025 | 1 |
| NAWFA region | Total SLR1m to aquatic ecosystems (w true zeros) |  | RiskExtvalue(0.010796,0.0736,RiskName("NA SLR (w zeros)"),RiskLibrary(159,"AKPAVPPM","RiskLibraryLocal")) | -∞ | 0.053 | +∞ |
| NAWFA region | Total SLR1m to aquatic ecosystems (w true zeros) TRUNC |  | RiskExtvalue(0.010796,0.0736,RiskTruncate(0,1),RiskName("NA TOT SLR TRUNC"),RiskLibrary(160,"8EJ4BPUW","RiskLibraryLocal")) | 0.0 | 0.096 | 1 |
| NAWFA region | Total SLR1m Risk to HCVAE99 |  | RiskExtvalue(0.0034771,0.019795,RiskName("NA SLR HCVAE99 Tot risks"),RiskLibrary(77,"CKYNNBH6","RiskLibraryLocal")) | -∞ | 0.015 | +∞ |
| NAWFA region | Total SLR1m Risk to HCVAE99 TRUNC |  | RiskExtvalue(0.0034771,0.019795,RiskTruncate(0,1),RiskName("NA SLR HCVAE99 Tot risks TRUNC")) | 0.0 | 0.026 | 1 |

Table 6b (continue).

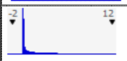
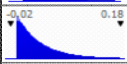
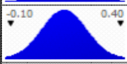
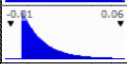
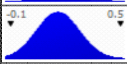
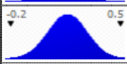
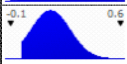
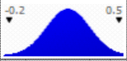
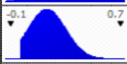
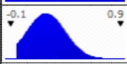
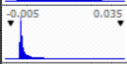
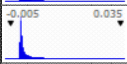
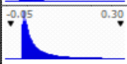
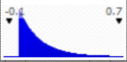
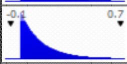
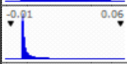
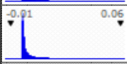
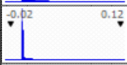
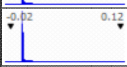
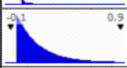
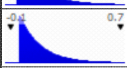
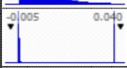
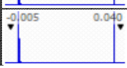
| (b) AWRC basin means | Attribute | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|
| AWRC basin means | Mean of mean Riverine ecosystem (km) |  | RiskLogistic(125.686,20.403,RiskFit("NA basin means Mean Riv L km","Chi-Sq"),RiskName("NA basin means Mean Riv L km")) | -∞ | 125.686 | +∞ |
| AWRC basin means | Mean of mean Palustrine ecosystem ($km^2$) |  | RiskBetaGeneral(0.35851,2.2894,0,13.495,RiskName("NA basin means Mean Pal km2"),RiskLibrary(232,"BQPY71YX","RiskLibraryLocal")) | 0 | 1.827136 | 13.495 |
| AWRC basin means | Mean of mean Lacustrine ecosystem ($km^2$) |  | RiskPearson5(2.9514,0.65311,RiskShift(-0.075671),RiskName("NA mean basin Mean Lac km2"),RiskLibrary(233,"K5MQ1P6J","RiskLibraryLocal")) | -0.075671 | 0.2590169 | +∞ |
| AWRC basin means | HCVAE99 (rescaled to 1.0) |  | RiskExpon(0.039518,RiskShift(-0.00074563),RiskName("NA basin means rescaled HCVAE99"),RiskLibrary(204,"KDHMD9G3","RiskLibraryLocal")) | 0.0 | 0.039 | +∞ |
| AWRC basin means | Catchment Disturbance Inedex (CDI) rescaled to 1.0 across region |  | RiskNormal(0.146514,0.092397,RiskName("NA basin means adjCDI"),RiskLibrary(205,"BCIX3GCC","RiskLibraryLocal")) | -∞ | 0.147 | +∞ |
| AWRC basin means | Flow Regime Disturbance Index (FRDI) |  | RiskExpon(0.011833,RiskShift(-0.00022327),RiskName("NA basin means FRDI"),RiskLibrary(206,"LNNMLC79","RiskLibraryLocal")) | 0.0 | 0.012 | +∞ |
| AWRC basin means | Development Risk Riverine |  | RiskNormal(0.16438,0.10756,RiskName("NA basin means DEV risks River"),RiskLibrary(131,"E8LXJNU4","RiskLibraryLocal")) | -∞ | 0.164 | +∞ |
| AWRC basin means | Development Risk Riverine TRUNC |  | RiskNormal(0.16438,0.10756,RiskTruncate(0,1),RiskName("NA basin means DEV Risk River TRUNC"),RiskLibrary(134,"TQUMVB1I","RiskLibraryLocal")) | 0.0 | 0.179 | 1 |
| AWRC basin means | Development Risk Palustrine |  | RiskNormal(0.16484,0.11363,RiskName("NA basin means DEV Palustrine"),RiskLibrary(132,"WF7DIK6V","RiskLibraryLocal")) | -∞ | 0.165 | +∞ |
| AWRC basin means | Development Risk Palustrine TRUNC |  | RiskNormal(0.16484,0.11363,RiskTruncate(0,1),RiskName("NA basin means DEV Palus TRUNC"),RiskLibrary(135,"K1NJ33YP","RiskLibraryLocal")) | 0.0 | 0.182 | 1 |
| AWRC basin means | Development Risk Lacustrine |  | RiskNormal(0.17744,0.12562,RiskName("NA basin means DEV Lacus"),RiskLibrary(133,"29YBP1Q9","RiskLibraryLocal")) | -∞ | 0.177 | +∞ |
| AWRC basin means | Development Risk Lacustrine TRUNC |  | RiskNormal(0.17744,0.12562,RiskTruncate(0,1),RiskName("NA basin means DEV Lacus TRUNC"),RiskLibrary(136,"G9K392G6","RiskLibraryLocal")) | 0.0 | 0.198 | 1 |
| AWRC basin means | Total Development Risk (w zeros) |  | RiskNormal(0.23965,0.15884,RiskName("DEV risk basin means TRUNC")) | -∞ | 0.240 | +∞ |
| AWRC basin means | Total Development Risk (w zeros) TRUNC |  | RiskNormal(0.23965,0.15884,RiskTruncate(0,1),RiskName("DEV risk basin means TRUNC"),RiskLibrary(173,"7WYVHWBE","RiskLibraryLocal")) | 0.0 | 0.261 | 1 |
| AWRC basin means | Total Development Risk to HCVAE99 |  | RiskInvgauss(0.0090683,0.00048599,RiskShift(-0.00012748),RiskName("NA basin means DEV HCVAE99"),RiskLibrary(140,"4UBNYBKX","RiskLibraryLocal")) | 0.0 | 0.009 | +∞ |
| AWRC basin means | Total Development Risk to HCVAE99 TRUNC |  | RiskInvgauss(0.0090683,0.00048599,RiskShift(-0.00012748),RiskTruncate(0,1),RiskName("NA basin means DEV HCVAE99 TRUNC"),RiskLibrary(142,"54JCC816","RiskLibraryLocal")) | -∞ | 0.009 | +∞ |
| AWRC basin means | SLR1m to sub-catchments |  | RiskLognorm(0.061747,0.13569,RiskShift(-0.0014542),RiskName("NA basin means P SLR"),RiskLibrary(203,"RVIY3N8K","RiskLibraryLocal")) | 0.0 | 0.060 | +∞ |
| AWRC basin means | SLR1m Risk Riverine |  | RiskPareto2(4358519.5,32044111.3,RiskName("NA basin means SLR River"),RiskLibrary(91,"AVA5CFRW","RiskLibraryLocal")) | 0.0 | 0.136 | +∞ |
| AWRC basin means | SLR1m Risk Riverine TRUNC |  | RiskPareto2(4358519.5,32044111.3,RiskTruncate(0,1),RiskName("NA basin means SLR River TRUNC"),RiskLibrary(97,"CYTHIJSU","RiskLibraryLocal")) | 0.0 | 0.135 | 1 |
| AWRC basin means | SLR1m Risk Palustrine |  | RiskInvgauss(0.018044,0.00090791,RiskShift(-0.00024182),RiskName("NA basin means SLR Pal"),RiskLibrary(92,"5HAB8FAL","RiskLibraryLocal")) | 0.0 | 0.018 | +∞ |
| AWRC basin means | SLR1m Risk Palustrine TRUNC |  | RiskInvgauss(0.018044,0.00090791,RiskShift(-0.00024182),RiskTruncate(0,1),RiskName("NA basin means SLR Pal TRUNC"),RiskLibrary(98,"FPZLLUHZ","RiskLibraryLocal")) | -∞ | 0.016 | +∞ |
| AWRC basin means | SLR1m Risk Lacustrine |  | RiskBetaGeneral(0.30583,15.183,0,0.87681,RiskFit("NA basin means SLR1 lac 2"),RiskName("NA basin means SLR1 lac 2")) | 0.0 | 0.017 | 0.9 |
| AWRC basin means | SLR1m Risk Lacustrine TRUNC |  | RiskBetaGeneral(0.30583,15.183,0,0.87681,RiskTruncate(0,1),RiskFit("NA basin means SLR1 lac 2 TRUNC"),RiskName("NA basin means SLR1 lac 2 TRUNC")) | 0.0 | 0.017 | 0.9 |
| AWRC basin means | Total SLR1m to aquatic ecosystems (w true zeros) |  | RiskExpon(0.18366,RiskShift(-0.0034652),RiskName("NA mean basins SLR Tot2 risks"),RiskLibrary(67,"Q57VHL4R","RiskLibraryLocal")) | 0.0 | 0.180 | +∞ |
| AWRC basin means | Total SLR1m to aquatic ecosystems (w true zeros) TRUNC |  | RiskExpon(0.1372,RiskShift(-0.0025888),RiskTruncate(0,1),RiskName("SLR risk basin means TRUNC"),RiskLibrary(172,"FZEDPLK2","RiskLibraryLocal")) | -∞ | 0.134 | +∞ |
| AWRC basin means | Total SLR1m Risk to HCVAE99 |  | RiskBetaGeneral(0.22721,0.77117,0,0.036258,RiskName("NA basin means SLR HCVAE99"),RiskLibrary(141,"98UTLXKP","RiskLibraryLocal")) | 0.0 | 0.008 | 0.04 |
| AWRC basin means | Total SLR1m Risk to HCVAE99 TRUNC |  | RiskBetaGeneral(0.22721,0.77117,0,0.036258,RiskTruncate(0,1),RiskName("NA basin means SLR HCVAE TRUNC"),RiskLibrary(143,"IQU3WMUW","RiskLibraryLocal")) | 0.0 | 0.008 | 0.04 |

Table 6c (continue).

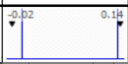
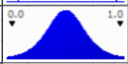
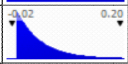
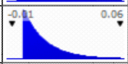
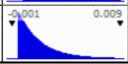
| (c) Selected basins with contrasting land use | Attribute | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|
| South Alligator River basin | Total Development Risk (w zeros) |  | RiskBetaGeneral(0.15147,0.6153,0,0.13103,RiskName("South Alligator Tot Dev Risk"),RiskLibrary(176,"EDLDWA6I","RiskLibraryLocal")) | 0.0 | 0.026 | 0.13 |
| South Alligator River basin | Total SLR1m to aquatic ecosystems (w true zeros) |  | RiskBetaGeneral(0.12412,0.63133,0,1,RiskName("South Alligator Tot SLR Risk"),RiskLibrary(177,"JGDX3PHB","RiskLibraryLocal")) | 0.0 | 0.164 | 1.00 |
| South Alligator River basin | Total Development Risk to HCVAE99 |  | RiskBetaGeneral(0.13179,1.1953,0,0.083398,RiskName("South Alligator Tot Dev risk HCVAE99"),RiskLibrary(179,"958BJ74D","RiskLibraryLocal")) | 0.0 | 0.008 | 0.08 |
| South Alligator River basin | Total SLR1m Risk to HCVAE99 |  | RiskBetaGeneral(0.11029,0.5933,0,0.16827,RiskName("South Alligator Tot SLR Risk HCVAE99"),RiskLibrary(186,"25U9KEYY","RiskLibraryLocal")) | 0.0 | 0.026 | 0.17 |
| Norman River basin | Total Development Risk (w zeros) |  | RiskLogistic(0.50253,0.10364,RiskName("Norman Tot Dev Risks"),RiskLibrary(181,"UHLI7VSM","RiskLibraryLocal")) | -∞ | 0.503 | +∞ |
| Norman River basin | Total SLR1m to aquatic ecosystems (w true zeros) |  | RiskExpon(0.044052,RiskShift(-0.00018054),RiskName("Norman Tot SLR Risk"),RiskLibrary(182,"EWHEMHJ7","RiskLibraryLocal")) | 0.0 | 0.044 | +∞ |
| Norman River basin | Total Development Risk to HCVAE99 |  | RiskExpon(0.012906,RiskShift(-0.0000528935),RiskName("Norman Tot Dev Risk HCVAE99"),RiskLibrary(183,"LEB97EU8","RiskLibraryLocal")) | 0.0 | 0.013 | +∞ |
| Norman River basin | Total SLR1m Risk to HCVAE99 |  | RiskExpon(0.0018256,RiskShift(-0.00000748213),RiskName("Norman Tot SLR Risk HCVAE99"),RiskLibrary(185,"FZFX6G7B","RiskLibraryLocal")) | 0.0 | 0.002 | +∞ |

Table 6d (continue).

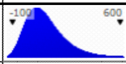
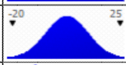
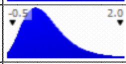
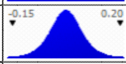
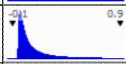
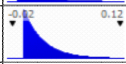
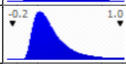
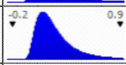
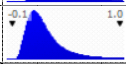
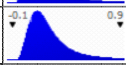
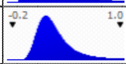
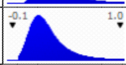
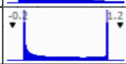
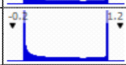
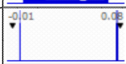
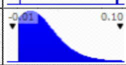
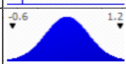
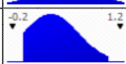
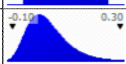
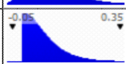
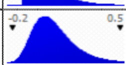
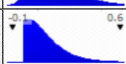
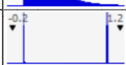
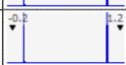
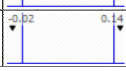
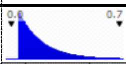
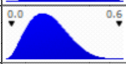
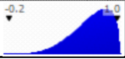
| (d) Finniss R basin | Attribute | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|
| Finniss River basin | Riverine ecosystem (km) |  | RiskExtvalue(75.065,93.6,RiskName("Finniss River length km"),RiskLibrary(37,"RWDZ4G75","RiskLibraryLocal")) | -∞ | 129.1 | +∞ |
| Finniss River basin | Palustrine ecosystem ($km^2$) |  | RiskNormal(2.989,7.9669,RiskName("Finniss Palus area km2"),RiskLibrary(39,"378JPAJZ","RiskLibraryLocal")) | -∞ | 2.989 | +∞ |
| Finniss River basin | Lacustrine ecosystem ($km^2$) |  | RiskExtvalue(0.099547,0.37163,RiskName("Finniss Lacus area km2"),RiskLibrary(41,"4SY26SK1","RiskLibraryLocal")) | -∞ | 0.314 | +∞ |
| Finniss River basin | HCVAE99 (rescaled 1.0) |  | RiskLogistic(0.025389,0.029197,RiskFit("Finniss rescaled HCVAE99","K-S"),RiskName("Finniss rescaled HCVAE99")) | -∞ | 0.025 | +∞ |
| Finniss River basin | Catchment Disturbance Inedex (CDI) rescaled to 1.0 across region |  | RiskInvgauss(0.17739,0.070472,RiskShift(-0.016083),RiskFit("Finniss adjCDI","A-D"),RiskName("Finniss adjCDI")) | 0.0 | 0.161 | +∞ |
| Finniss River basin | Flow Regime Disturbance Index (FRDI) |  | RiskExpon(0.022775,RiskShift(-0.00042971),RiskFit("Finniss_2 FRDI","Chi-Sq"),RiskName("Finniss_2 FRDI")) | 0.0 | 0.022 | +∞ |
| Finniss River basin | Development Risk Riverine |  | RiskPearson5(5.0504,1.5086,RiskShift(-0.11676),RiskName("Finniss DEV Risk River")) | -0.1 | 0.256 | +∞ |
| Finniss River basin | Development Risk Riverine TRUNC |  | RiskPearson5(5.0504,1.5086,RiskShift(-0.11676),RiskTruncate(0,1),RiskName("Finniss DEV Risk River TRUNC")) | -∞ | 0.239 | +∞ |
| Finniss River basin | Development Risk Palustrine |  | RiskLoglogistic(-0.014443,0.22799,2.5991,RiskName("Finniss Devel Risk Pal")) | 0.0 | 0.280 | +∞ |
| Finniss River basin | Development Risk Palustrine TRUNC |  | RiskLoglogistic(-0.014443,0.22799,2.5991,RiskTruncate(0,1),RiskName("Finniss Devel Risk Pal TRUNC")) | 0.0 | 0.252 | 1.00 |
| Finniss River basin | Development Risk Lacustrine |  | RiskLoglogistic(-0.045596,0.29168,3.2156,RiskName("Finniss DEV Risk Lacus")) | 0.0 | 0.298 | +∞ |
| Finniss River basin | Development Risk Lacustrine TRUNC |  | RiskLoglogistic(-0.045596,0.29168,3.2156,RiskTruncate(0,1),RiskName("Finniss DEV Risk Lacus TRUNC")) | 0.0 | 0.280 | 1.00 |
| Finniss River basin | Total Development Risk (w zeros) |  | RiskBetaGeneral(0.46916,0.78118,0,1,RiskName("FINNISS Tot2 Dev Risk"),RiskLibrary(199,"M3KPMRSW","RiskLibraryLocal")) | 0.0 | 0.375 | 1.00 |
| Finniss River basin | Total Development Risk (w zeros) TRUNC |  | RiskBetaGeneral(0.46916,0.78118,0,1,RiskTruncate(0,1),RiskName("FINNISS Tot2 Dev Risk")) | 0.0 | 0.375 | 1.00 |
| Finniss River basin | Total Development Risk to HCVAE99 |  | RiskBetaGeneral(0.12289,0.61372,0,0.074759,RiskName("FINNISS Tot Dev HCVAE99"),RiskLibrary(201,"SUQSLAXA","RiskLibraryLocal")) | 0.0 | 0.012 | 0.07 |
| Finniss River basin | Total Development Risk to HCVAE99 TRUNC |  | RiskLogistic(0.011498,0.014577,RiskTruncate(0,1),RiskName("Finniss HCVAE99 Dev risk TRUNC")) | 0.0 | 0.025 | 1.00 |
| Finniss River basin | SLR1m to sub-catchments |  | RiskBetaGeneral(0.24808,2.6644,0,1.141,RiskName("Finniss SLR1 Risk cpu TRUNC"),RiskTruncate(0,1)) | 0.0 | 0.097 | 1.00 |
| Finniss River basin | SLR1m Risk Riverine |  | RiskNormal(0.31912,0.32581,RiskName("Finniss SLR Risk River")) | -∞ | 0.319 | +∞ |
| Finniss River basin | SLR1m Risk Riverine TRUNC |  | RiskNormal(0.31912,0.32581,RiskTruncate(0,1),RiskName("Finniss SLR Risk River TRUNC")) | 0.0 | 0.400 | 1.00 |
| Finniss River basin | SLR1m Risk Palustrine |  | RiskExtvalue(0.0071993,0.056236,RiskName("Finniss SLR Risk Pal")) | -∞ | 0.040 | +∞ |
| Finniss River basin | SLR1m Risk Palustrine TRUNC |  | RiskExtvalue(0.0071993,0.056236,RiskTruncate(0,1),RiskName("Finniss SLR Risk Pal TRUNC")) | 0.0 | 0.073 | 1.00 |
| Finniss River basin | SLR1m Risk Lacustrine |  | RiskExtvalue(0.02335,0.099843,RiskName("Finniss SLR risk lacus")) | -∞ | 0.081 | +∞ |
| Finniss River basin | SLR1m Risk Lacustrine TRUNC |  | RiskExtvalue(0.02335,0.099843,RiskTruncate(0,1),RiskName("Finniss SLR risk lacus TRUNC")) | 0.0 | 0.133 | 1.00 |
| Finniss River basin | Total SLR1m to aquatic ecosystems (w true zeros) |  | RiskBetaGeneral(0.17268,0.30911,0,1,RiskName("FINNISS Tot2 SLR Risk"),RiskLibrary(200,"NQ82WDRH","RiskLibraryLocal")) | 0.0 | 0.358 | 1.00 |
| Finniss River basin | Total SLR1m to aquatic ecosystems (w true zeros) TRUNC |  | RiskBetaGeneral(0.17268,0.30911,0,1,RiskTruncate(0,1),RiskName("FINNISS Tot2 SLR Risk")) | 0.0 | 0.358 | 1.00 |
| Finniss River basin | Total SLR1m Risk to HCVAE99 |  | RiskBetaGeneral(0.11664,0.60412,0,0.1257,RiskName("FINNISS Tot SLR HCVAE99"),RiskLibrary(202,"3WM6N14C","RiskLibraryLocal")) | 0.0 | 0.020 | 0.13 |
| Finniss River basin | Total SLR1m Risk to HCVAE99 TRUNC |  | RiskBetaGeneral(0.11664,0.60412,0,0.1257,RiskTruncate(0,1),RiskName("Finniss HCVAE99 SLR risk TRUNC")) | 0.0 | 0.020 | 0.13 |

Table 6e (continue).

| (e) SLR & species distribution | Attribute | Graph | Function | Min | Mean | Max |
|---|---|---|---|---|---|---|
| NAWFA region | SLR1m effects on predicted turtle distribution |  | RiskPareto2(353646.2,2617374.5,RiskShift(0.076923),RiskName("NA Turtles SLR"),RiskLibrary(210,"PELRRA2H","RiskLibraryLocal")) | 0.1 | 0.212 | +∞ |
| NAWFA region | SLR1m effects on predicted fish distribution |  | RiskBetaGeneral(2.9928,5.5536,0.0031401,0.60652,RiskName("NA Fish SLR"),RiskLibrary(208,"I2QIPWHI","RiskLibraryLocal")) | 0.0 | 0.214 | 0.61 |
| NAWFA region | SLR1m effects on predicted waterbirds distribution |  | RiskBetaGeneral(3.8502,1.4536,-0.068646,0.98558,RiskName("NA Waterbirds SLR"),RiskLibrary(209,"G6ND8VGV","RiskLibraryLocal")) | -0.1 | 0.697 | 0.99 |

# APPENDIX B

Table 7 (Appendix B). Summary of mean basin threats and risks to aquatic ecosystems and HCVAE99 assets.

Variables in table: (1) number of sub-catchments in basin; (2) area ($km^2$) of sub-catchment units; (3) Catchment Disturbance Index (CDI); (4) re-scaled CDI; (5) Flow Regime Disturbance Index (FRDI); (6) River Disturbance Index (RDI) using the mean of CDI and FRDI (after Stein et al. 2002); (7) re-scaled RDI (rsCDI) using a joint probability equation (see text); (8) Development risk to Riverine ecosystems; (9) Development risk to Palustrine ecosystems; (10) Development risk to Lacustrine ecosystems; (11) total Development risk to aquatic ecosystems; (12) area ($km^2$) of sub-catchment units inundated by a projected 1m sea level rise (SLR) in 2100; (13) proportion of coastal sub-catchment units inundated by a 1m SLR; (14) SLR risk to Riverine ecosystems; (15) SLR risk to Plaustrine ecosystems; (16) SLR risk to Lacustrine ecosystems; (17) SLR risk to all aquatic ecosystems combined; (18) HCVAE99 (sum of all criteria met ; Kennard 2010), and (19) re-scaled to 1.0; and (20) Development and (21) SLR risks to HCVAE99 assets, respectively.

APPENDIX B

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AWRC_BASIN | N sub-catchments | A pu $km^2$ | CDI | rsCDI | FRDI | RDI | rsRDI | P Riv Dev | P Pal Dev | P Lac Dev | P Tot Dev | Apu SLR $km^2$ | P SLR | P Riv SLR | P Pal SLR | P Lac SLR | P Tot SLR | HCVAE99 | rsHCVAE99 | P H99 Dev | P H99 SLR |
| ADELAIDE RIVER | 36 | 7,449 | 0.169 | 0.249 | 0.132 | 0.151 | 0.348 | 0.346 | 0.341 | 0.402 | 0.742 | 2.21 | 0.027 | 0.147 | 0.002 | 0.011 | 0.154 | 0.333 | 0.083 | 0.064 | 0.001 |
| ARCHER RIVER | 83 | 13,899 | 0.090 | 0.132 | 0.000 | 0.045 | 0.132 | 0.137 | 0.122 | 0.125 | 0.337 | 0.27 | 0.026 | 0.086 | 0.012 | 0.002 | 0.099 | 0.060 | 0.015 | 0.007 | 0.000 |
| BLYTH RIVER | 50 | 9,022 | 0.001 | 0.001 | 0.000 | 0.000 | 0.001 | 0.002 | 0.001 | 0.001 | 0.004 | 5.75 | 0.148 | 0.307 | 0.009 | 0.036 | 0.318 | 0.220 | 0.055 | 0.000 | 0.001 |
| BUCKINGHAM RIVER | 63 | 8,388 | 0.004 | 0.005 | 0.000 | 0.002 | 0.005 | 0.007 | 0.005 | 0.001 | 0.013 | 4.14 | 0.200 | 0.288 | 0.000 | 0.031 | 0.306 | 0.079 | 0.020 | 0.000 | 0.000 |
| CALVERT RIVER | 41 | 10,372 | 0.150 | 0.221 | 0.000 | 0.075 | 0.221 | 0.227 | 0.237 | 0.218 | 0.539 | 2.77 | 0.031 | 0.085 | 0.003 | 0.028 | 0.094 | 0.049 | 0.012 | 0.009 | 0.000 |
| CAPE LEVEQUE COAST | 105 | 22,583 | 0.105 | 0.155 | 0.000 | 0.053 | 0.155 | 0.209 | 0.139 | 0.189 | 0.447 | 0.57 | 0.008 | 0.094 | 0.001 | 0.038 | 0.122 | 0.010 | 0.002 | 0.001 | 0.000 |
| COLEMAN RIVER | 66 | 13,062 | 0.108 | 0.160 | 0.000 | 0.054 | 0.160 | 0.170 | 0.171 | 0.167 | 0.427 | 0.44 | 0.024 | 0.075 | 0.018 | 0.005 | 0.093 | 0.242 | 0.061 | 0.000 | 0.000 |
| DALY RIVER | 283 | 53,595 | 0.123 | 0.181 | 0.009 | 0.066 | 0.188 | 0.196 | 0.208 | 0.194 | 0.486 | 0.07 | 0.002 | 0.016 | 0.001 | 0.006 | 0.022 | 0.046 | 0.011 | 0.007 | 0.000 |
| DRYSDALE RIVER | 129 | 25,346 | 0.084 | 0.124 | 0.000 | 0.042 | 0.124 | 0.128 | 0.115 | 0.081 | 0.290 | 0.26 | 0.008 | 0.054 | 0.000 | 0.008 | 0.060 | 0.016 | 0.004 | 0.001 | 0.000 |
| DUCIE RIVER | 49 | 6,717 | 0.059 | 0.086 | 0.000 | 0.029 | 0.086 | 0.092 | 0.093 | 0.366 | 0.478 | 0.74 | 0.018 | 0.196 | 0.000 | 0.000 | 0.196 | 0.000 | 0.000 | 0.000 | 0.000 |
| EAST ALLIGATOR RIVER | 85 | 15,392 | 0.002 | 0.003 | 0.000 | 0.001 | 0.003 | 0.003 | 0.004 | 0.003 | 0.010 | 2.63 | 0.043 | 0.181 | 0.001 | 0.040 | 0.216 | 0.400 | 0.100 | 0.001 | 0.001 |
| EMBLEY RIVER | 41 | 4,621 | 0.074 | 0.109 | 0.000 | 0.037 | 0.109 | 0.149 | 0.139 | 0.117 | 0.353 | 0.59 | 0.008 | 0.125 | 0.025 | 0.004 | 0.148 | 0.000 | 0.000 | 0.000 | 0.000 |
| FINNISS RIVER | 53 | 9,167 | 0.110 | 0.161 | 0.023 | 0.066 | 0.180 | 0.213 | 0.216 | 0.214 | 0.515 | 5.78 | 0.094 | 0.271 | 0.038 | 0.044 | 0.291 | 0.075 | 0.019 | 0.010 | 0.000 |
| FITZMAURICE RIVER | 58 | 10,146 | 0.033 | 0.049 | 0.000 | 0.017 | 0.049 | 0.050 | 0.082 | 0.012 | 0.139 | 7.90 | 0.136 | 0.189 | 0.000 | 0.007 | 0.193 | 0.000 | 0.000 | 0.000 | 0.000 |
| FITZROY RIVER (QLD) | 481 | 94,107 | 0.171 | 0.251 | 0.040 | 0.105 | 0.280 | 0.295 | 0.333 | 0.325 | 0.682 | 0.03 | 0.001 | 0.007 | 0.000 | 0.000 | 0.007 | 0.019 | 0.005 | 0.003 | 0.000 |
| FLINDERS RIVER | 556 | 109,480 | 0.219 | 0.323 | 0.233 | 0.226 | 0.481 | 0.481 | 0.505 | 0.521 | 0.877 | 0.51 | 0.011 | 0.013 | 0.001 | 0.006 | 0.016 | 0.038 | 0.009 | 0.009 | 0.000 |
| GILBERT RIVER | 257 | 46,237 | 0.198 | 0.292 | 0.033 | 0.116 | 0.315 | 0.318 | 0.313 | 0.325 | 0.684 | 0.68 | 0.024 | 0.059 | 0.004 | 0.009 | 0.062 | 0.043 | 0.011 | 0.008 | 0.000 |
| GOOMADEER RIVER | 31 | 5,503 | 0.002 | 0.003 | 0.000 | 0.001 | 0.003 | 0.003 | 0.005 | 0.008 | 0.017 | 2.23 | 0.049 | 0.308 | 0.001 | 0.058 | 0.329 | 0.161 | 0.040 | 0.000 | 0.000 |
| GOYDER RIVER | 65 | 10,462 | 0.001 | 0.002 | 0.000 | 0.001 | 0.002 | 0.002 | 0.002 | 0.003 | 0.006 | 1.71 | 0.067 | 0.074 | 0.000 | 0.009 | 0.079 | 0.092 | 0.023 | 0.000 | 0.000 |
| HOLROYD RIVER | 60 | 10,304 | 0.132 | 0.194 | 0.000 | 0.066 | 0.194 | 0.197 | 0.208 | 0.214 | 0.500 | 0.05 | 0.019 | 0.031 | 0.000 | 0.000 | 0.032 | 0.067 | 0.017 | 0.000 | 0.000 |
| ISDELL RIVER | 112 | 19,532 | 0.103 | 0.151 | 0.000 | 0.051 | 0.151 | 0.158 | 0.184 | 0.138 | 0.408 | 0.85 | 0.020 | 0.073 | 0.001 | 0.000 | 0.074 | 0.000 | 0.000 | 0.000 | 0.000 |
| JARDINE RIVER | 13 | 3,179 | 0.109 | 0.161 | 0.000 | 0.055 | 0.161 | 0.161 | 0.268 | 0.442 | 0.657 | 0.15 | 0.001 | 0.031 | 0.003 | 0.001 | 0.035 | 0.538 | 0.135 | 0.015 | 0.000 |
| KEEP RIVER | 78 | 11,869 | 0.115 | 0.169 | 0.000 | 0.057 | 0.169 | 0.194 | 0.188 | 0.224 | 0.492 | 19.91 | 0.258 | 0.278 | 0.026 | 0.019 | 0.289 | 0.013 | 0.003 | 0.002 | 0.000 |
| KING EDWARD RIVER | 88 | 17,266 | 0.083 | 0.122 | 0.000 | 0.042 | 0.122 | 0.138 | 0.164 | 0.182 | 0.411 | 0.25 | 0.006 | 0.057 | 0.000 | 0.011 | 0.067 | 0.000 | 0.000 | 0.000 | 0.000 |
| KOOLATONG RIVER | 50 | 7,521 | 0.018 | 0.026 | 0.000 | 0.009 | 0.026 | 0.035 | 0.009 | 0.008 | 0.051 | 1.97 | 0.040 | 0.172 | 0.010 | 0.061 | 0.209 | 0.040 | 0.010 | 0.000 | 0.000 |
| LEICHHARDT RIVER | 170 | 33,718 | 0.192 | 0.282 | 0.059 | 0.125 | 0.325 | 0.325 | 0.308 | 0.316 | 0.681 | 1.63 | 0.027 | 0.037 | 0.006 | 0.003 | 0.042 | 0.059 | 0.015 | 0.012 | 0.000 |
| LENNARD RIVER | 80 | 14,737 | 0.144 | 0.211 | 0.000 | 0.072 | 0.211 | 0.219 | 0.236 | 0.264 | 0.561 | 0.39 | 0.015 | 0.072 | 0.000 | 0.000 | 0.072 | 0.000 | 0.000 | 0.000 | 0.000 |
| LIMMEN BIGHT RIVER | 89 | 15,919 | 0.100 | 0.147 | 0.000 | 0.050 | 0.147 | 0.152 | 0.150 | 0.144 | 0.383 | 1.12 | 0.022 | 0.048 | 0.000 | 0.000 | 0.048 | 0.000 | 0.000 | 0.000 | 0.000 |
| LIVERPOOL RIVER | 35 | 8,940 | 0.001 | 0.001 | 0.000 | 0.000 | 0.001 | 0.001 | 0.002 | 0.000 | 0.003 | 1.95 | 0.043 | 0.189 | 0.035 | 0.069 | 0.240 | 0.229 | 0.057 | 0.000 | 0.000 |
| MARY RIVER (NT) | 53 | 8,127 | 0.078 | 0.115 | 0.000 | 0.039 | 0.115 | 0.124 | 0.131 | 0.158 | 0.359 | 1.24 | 0.044 | 0.067 | 0.001 | 0.004 | 0.068 | 0.151 | 0.038 | 0.025 | 0.000 |
| McARTHUR RIVER | 101 | 19,101 | 0.166 | 0.245 | 0.000 | 0.083 | 0.245 | 0.247 | 0.248 | 0.259 | 0.581 | 1.69 | 0.023 | 0.073 | 0.000 | 0.000 | 0.073 | 0.010 | 0.002 | 0.000 | 0.000 |
| MITCHELL RIVER (QLD) | 368 | 71,504 | 0.178 | 0.262 | 0.018 | 0.098 | 0.275 | 0.278 | 0.276 | 0.294 | 0.631 | 0.34 | 0.017 | 0.044 | 0.003 | 0.006 | 0.047 | 0.082 | 0.020 | 0.002 | 0.000 |
| MORNING INLET | 22 | 3,532 | 0.166 | 0.245 | 0.007 | 0.087 | 0.250 | 0.250 | 0.262 | 0.233 | 0.576 | 38.50 | 0.400 | 0.475 | 0.212 | 0.188 | 0.605 | 0.045 | 0.011 | 0.008 | 0.002 |
| MOYLE RIVER | 35 | 6,920 | 0.002 | 0.003 | 0.000 | 0.001 | 0.003 | 0.004 | 0.004 | 0.006 | 0.014 | 5.28 | 0.118 | 0.297 | 0.039 | 0.019 | 0.340 | 0.057 | 0.014 | 0.000 | 0.001 |
| NICHOLSON RIVER | 259 | 51,097 | 0.127 | 0.186 | 0.001 | 0.064 | 0.187 | 0.190 | 0.219 | 0.158 | 0.467 | 3.96 | 0.037 | 0.046 | 0.005 | 0.005 | 0.050 | 0.054 | 0.014 | 0.010 | 0.001 |
| NORMAN RIVER | 244 | 50,408 | 0.182 | 0.268 | 0.015 | 0.098 | 0.279 | 0.290 | 0.291 | 0.301 | 0.648 | 1.02 | 0.021 | 0.040 | 0.002 | 0.008 | 0.044 | 0.049 | 0.012 | 0.009 | 0.001 |
| ORD RIVER | 294 | 55,867 | 0.158 | 0.232 | 0.051 | 0.104 | 0.271 | 0.274 | 0.295 | 0.251 | 0.617 | 1.31 | 0.014 | 0.018 | 0.004 | 0.000 | 0.020 | 0.041 | 0.010 | 0.006 | 0.000 |
| PENTECOST RIVER | 147 | 29,482 | 0.121 | 0.178 | 0.000 | 0.060 | 0.178 | 0.178 | 0.151 | 0.178 | 0.426 | 2.28 | 0.025 | 0.064 | 0.000 | 0.000 | 0.064 | 0.007 | 0.002 | 0.000 | 0.000 |
| PRINCE REGENT RIVER | 82 | 14,727 | 0.047 | 0.069 | 0.000 | 0.023 | 0.069 | 0.070 | 0.036 | 0.029 | 0.129 | 0.78 | 0.012 | 0.120 | 0.000 | 0.000 | 0.120 | 0.000 | 0.000 | 0.000 | 0.000 |
| ROBINSON RIVER | 59 | 11,132 | 0.123 | 0.181 | 0.000 | 0.062 | 0.181 | 0.187 | 0.193 | 0.158 | 0.448 | 5.65 | 0.159 | 0.223 | 0.002 | 0.018 | 0.224 | 0.000 | 0.000 | 0.000 | 0.000 |
| ROPER RIVER | 398 | 78,431 | 0.092 | 0.135 | 0.000 | 0.046 | 0.135 | 0.145 | 0.124 | 0.128 | 0.347 | 0.82 | 0.015 | 0.015 | 0.003 | 0.006 | 0.020 | 0.030 | 0.008 | 0.000 | 0.000 |
| ROSIE RIVER | 32 | 5,071 | 0.136 | 0.200 | 0.000 | 0.068 | 0.200 | 0.207 | 0.204 | 0.234 | 0.516 | 3.02 | 0.097 | 0.341 | 0.000 | 0.000 | 0.341 | 0.000 | 0.000 | 0.000 | 0.000 |
| SANDY DESERT | 13 | 3,430 | 0.175 | 0.258 | 0.000 | 0.088 | 0.258 | 0.258 | | 0.258 | 0.449 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| SETTLEMENT CREEK | 102 | 17,319 | 0.173 | 0.254 | 0.000 | 0.087 | 0.255 | 0.273 | 0.263 | 0.289 | 0.619 | 4.06 | 0.137 | 0.237 | 0.047 | 0.027 | 0.268 | 0.020 | 0.005 | 0.004 | 0.000 |
| SOUTH ALLIGATOR RIVER | 72 | 11,867 | 0.009 | 0.014 | 0.000 | 0.005 | 0.014 | 0.014 | 0.010 | 0.014 | 0.038 | 1.46 | 0.034 | 0.133 | 0.003 | 0.008 | 0.139 | 0.792 | 0.198 | 0.009 | 0.000 |
| STAATEN RIVER | 144 | 25,858 | 0.143 | 0.210 | 0.004 | 0.074 | 0.214 | 0.215 | 0.226 | 0.233 | 0.534 | 0.40 | 0.013 | 0.048 | 0.002 | 0.004 | 0.051 | 0.035 | 0.009 | 0.007 | 0.000 |
| TOWNS RIVER | 28 | 5,397 | 0.015 | 0.022 | 0.000 | 0.007 | 0.022 | 0.026 | 0.025 | 0.024 | 0.073 | 6.26 | 0.183 | 0.197 | 0.000 | 0.032 | 0.228 | 0.000 | 0.000 | 0.000 | 0.000 |
| VICTORIA RIVER | 436 | 78,485 | 0.126 | 0.186 | 0.000 | 0.063 | 0.186 | 0.189 | 0.185 | 0.199 | 0.470 | 0.93 | 0.006 | 0.015 | 0.000 | 0.000 | 0.015 | 0.011 | 0.003 | 0.001 | 0.000 |
| WALKER RIVER | 53 | 9,540 | 0.005 | 0.007 | 0.000 | 0.002 | 0.007 | 0.007 | 0.007 | 0.006 | 0.020 | 2.18 | 0.048 | 0.192 | 0.034 | 0.039 | 0.225 | 0.000 | 0.000 | 0.000 | 0.000 |
| WATSON RIVER | 24 | 4,579 | 0.113 | 0.167 | 0.000 | 0.057 | 0.167 | 0.167 | 0.179 | 0.154 | 0.422 | 0.36 | 0.003 | 0.104 | 0.007 | 0.043 | 0.128 | 0.000 | 0.000 | 0.000 | 0.000 |
| WENLOCK RIVER | 34 | 7,518 | 0.135 | 0.198 | 0.000 | 0.067 | 0.198 | 0.210 | 0.217 | 0.203 | 0.507 | 0.03 | 0.000 | 0.013 | 0.000 | 0.000 | 0.013 | 0.118 | 0.029 | 0.009 | 0.000 |
| WILDMAN RIVER | 24 | 4,782 | 0.058 | 0.086 | 0.000 | 0.029 | 0.086 | 0.098 | 0.114 | 0.175 | 0.341 | 2.16 | 0.060 | 0.275 | 0.002 | 0.004 | 0.275 | 0.042 | 0.010 | 0.000 | 0.000 |
| WISO | 62 | 14,222 | 0.051 | 0.076 | 0.000 | 0.026 | 0.076 | 0.204 | | 0.260 | 0.410 | 0.00 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Mean** | **121** | **22,772** | **0.100** | **0.147** | **0.012** | **0.056** | **0.155** | **0.164** | **0.165** | **0.177** | **0.393** | **2.85** | **0.054** | **0.125** | **0.011** | **0.017** | **0.137** | **0.082** | **0.021** | **0.005** | **0.000** |
| **Max** | **556** | **109,480** | **0.22** | **0.32** | **0.23** | **0.23** | **0.48** | **0.48** | **0.51** | **0.52** | **0.88** | **38.50** | **0.40** | **0.48** | **0.21** | **0.19** | **0.61** | **0.79** | **0.20** | **0.06** | **0.00** |
| **Min** | **13** | **3,179** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** | **0.00** |

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