Targeted analysis of the linkages between river runoff and risks for crown-of-thorns starfish outbreaks in the Northern GBR

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1 Introduction

Background

Coral cover on the Great Barrier Reef (GBR) has declined by half since 1985, with 42% of the observed decline attributed to coral predation by Crown-of-Thorns Seastar (De'ath et al., 2012). Cyclones and coral bleaching are the main causes of the additional mortality. Crown-of-Thorns Seastar (COTS) outbreaks are therefore a significant risk factor for the health and biodiversity status of the GBR. Over the last 50 years, COTS populations have exhibited a cyclic pattern of abundance characterized by large outbreaks at approximately 15 year intervals. The underlying cause(s) for the outbreaks are not fully resolved, and the extent to which human activities influence the occurrence of outbreaks remains controversial.

A recent study linking river runoff and risks for Crown-of-Thorns Seastar outbreaks in the Northern GBR (Furnas et al., 2013) examined data from a variety of experimental, modelling and observational studies and concluded that there was strong circumstantial evidence to support the hypothesis that COTS primary outbreaks in the Northern GBR are initiated by episodes of greatly enhanced larval survival during conditions of increased food availability for the filter-feeding pelagic larval stages. Enhanced regional chlorophyll concentrations in the Northern GBR during the early summer COTS spawning period were examined in the context of upwelling activity, rainfall and river runoff volumes, with analysis suggesting that wet season rainfall and river runoff has a greater influence on regional chlorophyll than upwelling activity (Furnas et al., 2013). Hydrodynamic modelling was used to estimate the volumetric contributions of significant rivers between the Daintree (16°S) and Burdekin (19°S) to the source outbreak region, and when coupled with estimates of end of river loads of dissolved inorganic nitrogen (DIN), were used to rank the individual DIN contributions from each river to regional DIN pool in the outbreak region. The modelling produced a quantitative identification of high or extended exposure to river plumes and provided a basis for prioritizing catchments for management attention, which informed an assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef (Brodie et al., 2013). However a limitation of the modelling was that it was only undertaken for the 2010-2011 wet season, which was a year with above average river flows. The dynamics and dispersion rates of river plumes are known to vary significantly from year to year in response to prevailing weather and oceanographic conditions at the time (e.g. King et al., 2002), and the modelling results and the river ranking based on 1 year of simulation may, therefore, not be representative of more typical conditions.

We present here an extension of the application of hydrodynamic modelling to elucidate linkages between river runoff to the north-central GBR (14-17°S) for four recent wet seasons (2008-09, 2010-11, 2011-12, 2012-13) that have preceded the recent incipient COTS outbreak in the Cairns to Lizard Island region of the GBR lagoon. We combine hydrodynamic modelling results with recent estimates of riverine DIN loads to assess and rank the relative contributions of major rivers which have discharges influencing the COTS outbreak region.

2 Data Sources and Methods

The methods adopted for this study follow that of Furnas et al. (2013).

Hydrodynamic modelling and tracer experiments

Hydrodynamic models provide a valuable tool for identifying, quantifying and communicating the spatial impact of discharges from various rivers into the GBR lagoon. Hydrodynamic models can simulate the three-dimensional transport and fate of material delivered to the marine environment, and deliver benefits over traditional static observations of river plume distributions. Whilst aerial and remote sensing can track the visual extent of river plumes, it is generally difficult to quantify the contribution of individual rivers to the overall observed spatial impact. The impact of the rivers is often confounded by a number of factors including: plumes from adjacent rivers which spatially overlap and mix; inputs of low salinity tropical water advected from the north and low surface salinity due to rainfall, which is rapidly mixed. Numerical models provide a number of solutions to this problem. During flood events, discharges of freshwater are resolved by the model's salinity solution. Passive tracers overcome the problems of using salinity alone as a tracer, as they allow the freshwater from the individual rivers to be tagged and assessed. Passive tracers act as virtual markers, and are conservatively advected and diffused in an identical fashion to physical variables such as temperature and salinity, but play no dynamic role in physical or biogeochemical processes. Importantly, simulation of the transport of unique tracers 'released' from different rivers enables the identification of marine regions influenced by individual catchments, and provides insight into the mixing and retention of river water along various regions with in the GBR lagoon (e.g. Brinkman et al., 2002; Luick et al., 2007).

A suite of hydrodynamic models are currently being applied to the GBR as part of the eReefs project (see http://www.bom.gov.au/environment/activities/coastal-info.shtml for more info), based primarily on the SHOC (Sparse Hydrodynamic Ocean Code; Herzfeld et al., 2006, (http://www.emg.cmar.csiro.au/www/en/emg/software/EMS/hydrodynamics.html) hydrodynamic model. SHOC is a general purpose model (Herzfeld, 2006), applicable on spatial scales ranging from estuaries to regional ocean domains. It is a three-dimensional finite-difference hydrodynamic model, based on the primitive equations. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracer concentrations, mixing coefficients and sea-level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and rainfall fluxes and open-boundary conditions such as tides, low frequency ocean currents and riverine inputs. For this study we used outputs from the regional application of SHOC to the GBR. This application has a horizontal spatial resolution of ~4 km, with a model grid size of 180 x 600 with 48 vertical layers with 1 m resolution at the surface.

Bathymetry for the model is sourced from the digital elevation model of the GBR produced at 100 m spatial resolution (Beaman, 2010; http://www.deepreef.org). In the northern limits of the domain this is supplemented by the GA 2009 bathymetry (Geoscience Australia, 2009). The 4 km model is forced with the global model OMAPS data (http://www.bom.gov.au/bluelink/products/prod_oceanmaps.html) on the open oceanic boundaries, where tidal elevations are also imposed. Surface atmospheric fluxes comprising momentum, heat and freshwater sources are obtained from the ACCESS meteorological model run operationally by BoM (http://www.bom.gov.au/nwp/doc/access/NWPData.shtml).

River flows input into the models (Table 1) were obtained from the DERM gauging network (http://www.derm.qld.gov.au/water/monitoring/current_data). The Fly River in Papua New Guinea is also included due to its high discharge adjacent to the far-northern GBR, with consistent average flows over the year of 6,000 $m^3 s^{-1}$. The volumes of flows and associated parameters associated with these rivers (temperature and salinity) are input into the model with prescribed concentrations (salinity = 0, temperature = ambient).

Table 1 Rivers included in the wet season hindcast simulation for 2008-09, 2010-11, 2011-12, 2012-13 wet seasons. Rivers in which passive tracers were released are shaded.

Normanby River	Daintree River
Barron River	Mulgrave-Russell Rivers
Johnstone River	Tully River
Herbert River	Haughton River
Burdekin River	Don River
O'Connell River	Pioneer River
Fitzroy River	Burnett River
Mary River	Fly River
Calliope	Boyne
Caboolture River	Pine River
Brisbane River	Logan River

For this study, hindcast simulations were performed for the wet season, which we considered to be the period from 01 November until 31 March of the following year. Simulations were performed for the 2008-09, 2010-11, 2011-12, 2012-13 wet seasons. For each simulated wet season, river-tagged passive tracers were released from each of the major rivers between the Burdekin River and the Normanby River at a rate proportional to discharge. The discharge concentration of each river's unique tracer was set at 1.0 at the river mouth, while the starting tracer concentration in the GBR Lagoon (time = 0 for each wet season) was set to 0.0.

River exposure index

Model simulations of the 3-dimensional distributions of passive tracers were analyzed to produce weekly estimates of cumulative exposure to tracers above a threshold of 1% of the source concentration.

Here we define a cumulative exposure index that integrates the tracer concentration above a defined threshold. It is a cumulative measurement of the exposure concentration and duration of exposure to dissolved inputs from individual river sources. It is expressed as **Concentration x Days** (Conc.Days)

For every location in the model domain cumulative exposure is calculated as follows:

$$\text{Conc.Days} = \sum_{t=0}^{T} \text{Conc}_{exceedance} * \text{t}$$

where

$$\text{Conc}_{exceedance} = \begin{cases} \text{Conc(t) - Conc}_{threshold}, & \text{where Conc(t)} > \text{Conc}_{threshold} \\ 0, & \text{where Conc(t)} \leq \text{Conc}_{threshold} \end{cases}$$

and $\text{Conc}_{threshold}$ is the defined here as 1% of the source concentration, Conc(t) represents the time-varying tracer concentration, and t is time in days from the beginning of the wet season (t_0 = 01 November), and $T_{\text{end of wet season}}$ = 31 March. Cumulative exposure is calculated for each grid point in the model domain.

Using this representation, the exposure index integrates both concentration above a defined threshold and the duration of exposure. For example, an exposure of 20 days at a concentration of 1% above the threshold would produce an index value of 0.2, which is equivalent to 10 days exposure at 2% above the concentration threshold. This index provides a consistent approach to assess relative differences in exposure of GBR shelf waters to inputs from various rivers. Spatial maps of river exposure indices were calculated for each of the target rivers for each of the wet seasons simulated by the model.

Relative contributions of individual rivers to the COTS initiation region between Cairns and Lizard Island were calculated based on the total cumulative exposure index, aggregated and summed spatially in latitudinal bands covering the region of interest to generate a single estimate of volumetric exposure for each river, for each year. For this calculation, we define the COTS outbreak region to be the region that lies between latitudes 17° - 14.5°S. Estimates of the relative contribution of freshwater discharge from individual rivers to the total outbreak initiation region (14.5-17°S) were normalized against the largest discharge into this region, on a year by year basis. For all years that were simulated, the Daintree River delivered the largest freshwater source wholly within the initiation region, and all flows were normalised to the Daintree discharge for the year of simulation. Rivers were ranked based on their normalised volumetric contributions to the outbreak region.

Because it is the contained nutrients (N,P,Si, etc.) in river runoff rather than freshwater *per se* which regulates phytoplankton growth and biomass, the major rivers influencing the outbreak area were also ranked on the basis of their estimated DIN (dissolved inorganic nitrogen = NH_4^++NO_2^-+NO_3^-) inputs to the Cairns-Lizard Island region.

Using modern estimates of DIN loads (see following subsections) from important rivers influencing the initiation region and estimates of the proportion of riverine freshwater inputs into the region derived from the tracer exposures, estimates of river-sourced DIN inputs into the COTS outbreak region were calculated .

River Discharge

For estimates of river flows and runoff volumes likely to affect the risk area for COTS outbreaks, we considered runoff from the Daintree (mean annual discharge ~ 1.3 Km^3), Barron (~0.8 Km^3), Mulgrave-Russell (~3.6 Km^3), Johnstone (~4.7 Km^3), Tully (~3.3 Km^3), Herbert (~4.0 Km^3) and Burdekin Rivers (~10.3 Km^3). Daily river discharges (ML day^{-1}) were obtained from the Queensland Department of Environment and Resource Management (DERM) for the 2008-09, 2010-11, 2011-12, 2012-13 wet seasons. Estimates of annual discharge from individual rivers over this period were made from integrations of daily flows from 1 October to 30 September (water year). Because COTS spawn in the early summer, integrations of discharge likely to affect pelagic COTS larvae were also done from 1 November to 28 February. For the purpose of integrating discharges, gaps in flow records for individual rivers were filled. Short gaps were filled by linear interpolation of daily flows across gaps. Longer gaps were filled using regressions derived between daily flows in a particular river and flows in adjacent rivers with nominally similar rainfall and catchment runoff characteristics (e.g. Tully and Johnstone Rivers) on the premise that integrating reasonable, if imprecise estimates of flows across a gap is better than integrating “0’s”.

DIN Loading

Estimates of annual DIN loads from regional rivers for the period 1999-2013 were obtained from Tropwater (Lewis et al. 2014). DIN loads based on event mean concentrations (EMCs - (ug/L)) were calculated for each water year (Oct 1 to Sept 30). Mean EMCs for the period 1999-2013 were calculated for each river and used in conjunction with the yearly volumetric contributions to assess DIN contributions to the outbreak region.

Risk scores

DIN exposure risk scores were calculated for each river, for each modelled year by multiplying the event mean concentration (ug/L) by the annual freshwater volume (normalised against the Daintree), multiplied by the % volumetric contribution to the outbreak initiation region. i.e. Risk Score = DIN Conc * FW volume * % contribution to source region. Using flows normalised to against the Daintree does not alter the risk rankings for each year, but allows comparison between years (and therefor the mean risk) as flows have been referenced to a consistent baseline. Mean risk scores were calculated for each river for the 4 modelled wet seasons. Rivers were then ranked based on their risk for individual years, and also based on the mean risk.

3 Results

Modelling flood plume exposure of the COTS initiation region

Total cumulative exposure of shelf waters in the central GBR during the 2010-2011 wet season to floods from individual rivers between the Burdekin and Normanby Rivers were calculated using numerical tracer experiments with a hydrodynamic model, and are presented below. Figures 1 to 4 present examples of exposure for the Burdekin, Tully, Johnstone and Russell-Mulgrave Rivers for 2008-2009 and 2010-2011 wet seasons. Exposure maps for the complete list of rivers and modelled wet seasons are presented in Appendix 1.

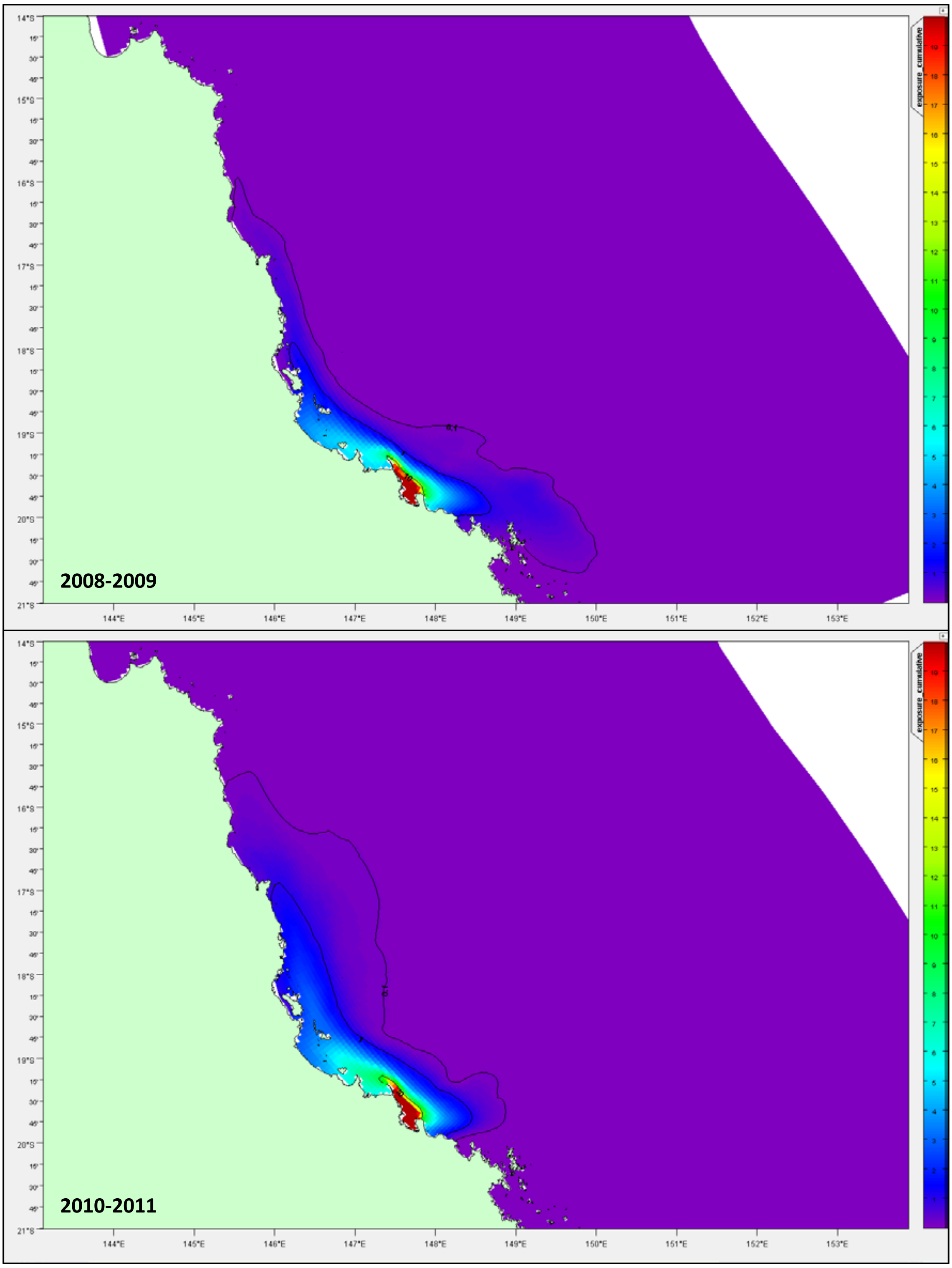

Figure 1 Cumulative exposure index for the Burdekin River over the 2008-2009 (top) and 2010-2011 (bottom) wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposures are 95 and 118 at the river mouth for 2008-2009 and 2010-2011, respectively. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

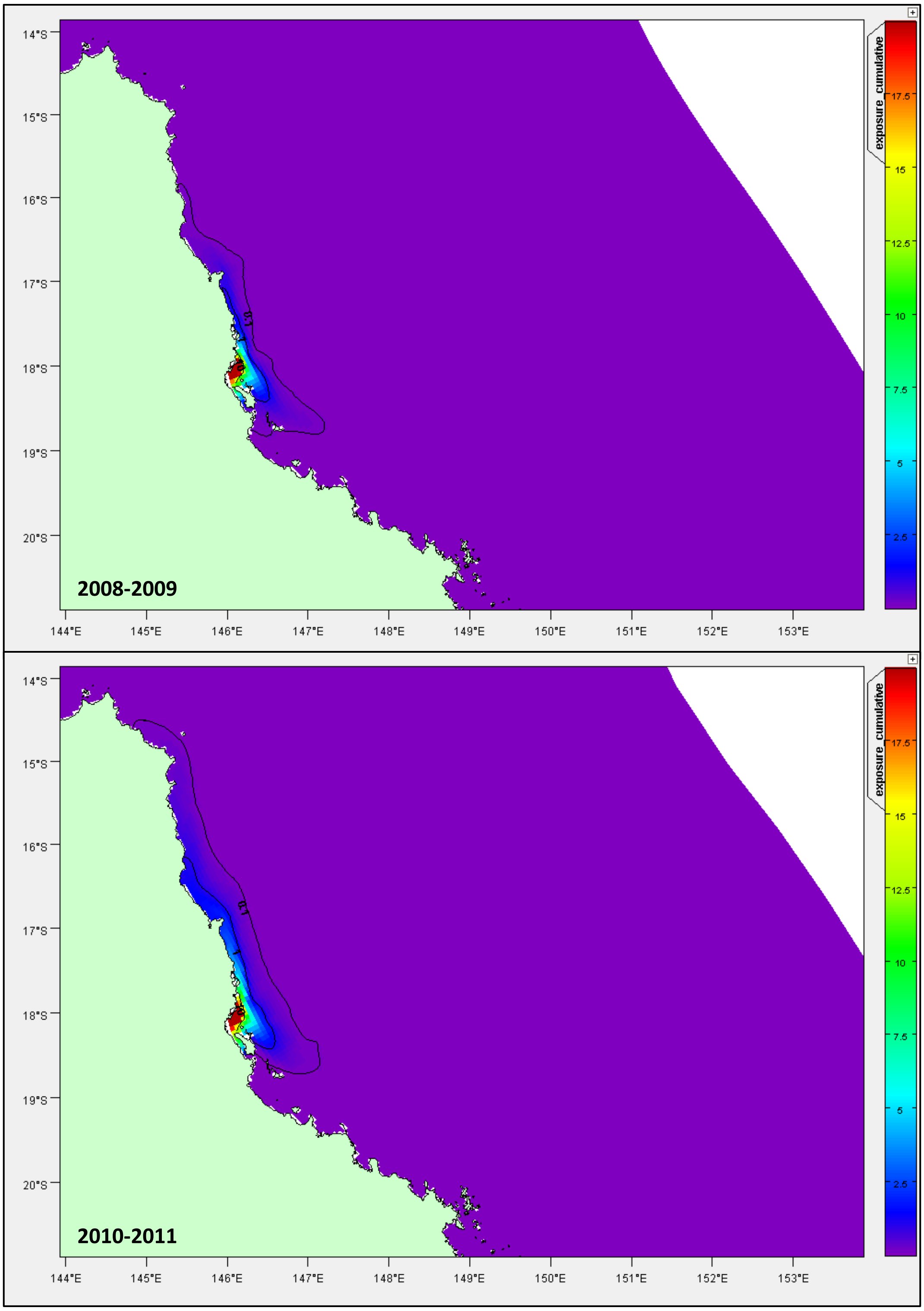

Figure 2 Cumulative exposure index for the Tully River over the 2008-2009 (top) and 2010-2011 (bottom) wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposures are 103 and 110 at the river mouth for 2008-2009 and 2010-2011, respectively. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

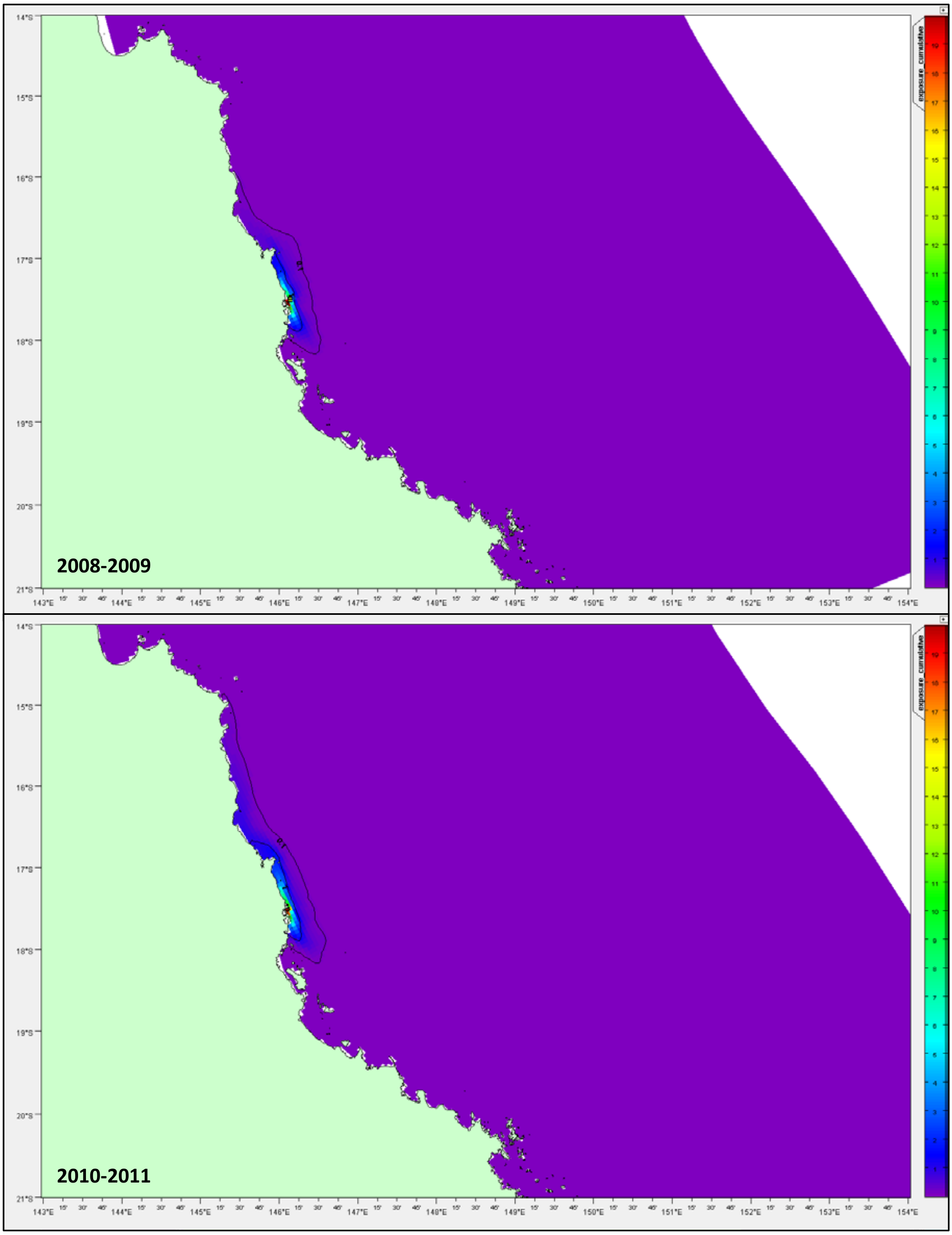

Figure 3 Cumulative exposure index for the Johnstone River over the 2008-2009 (top) and 2010-2011 (bottom) wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposures are 51 and 54 at the river mouth for 2008-2009 and 2010-2011, respectively. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

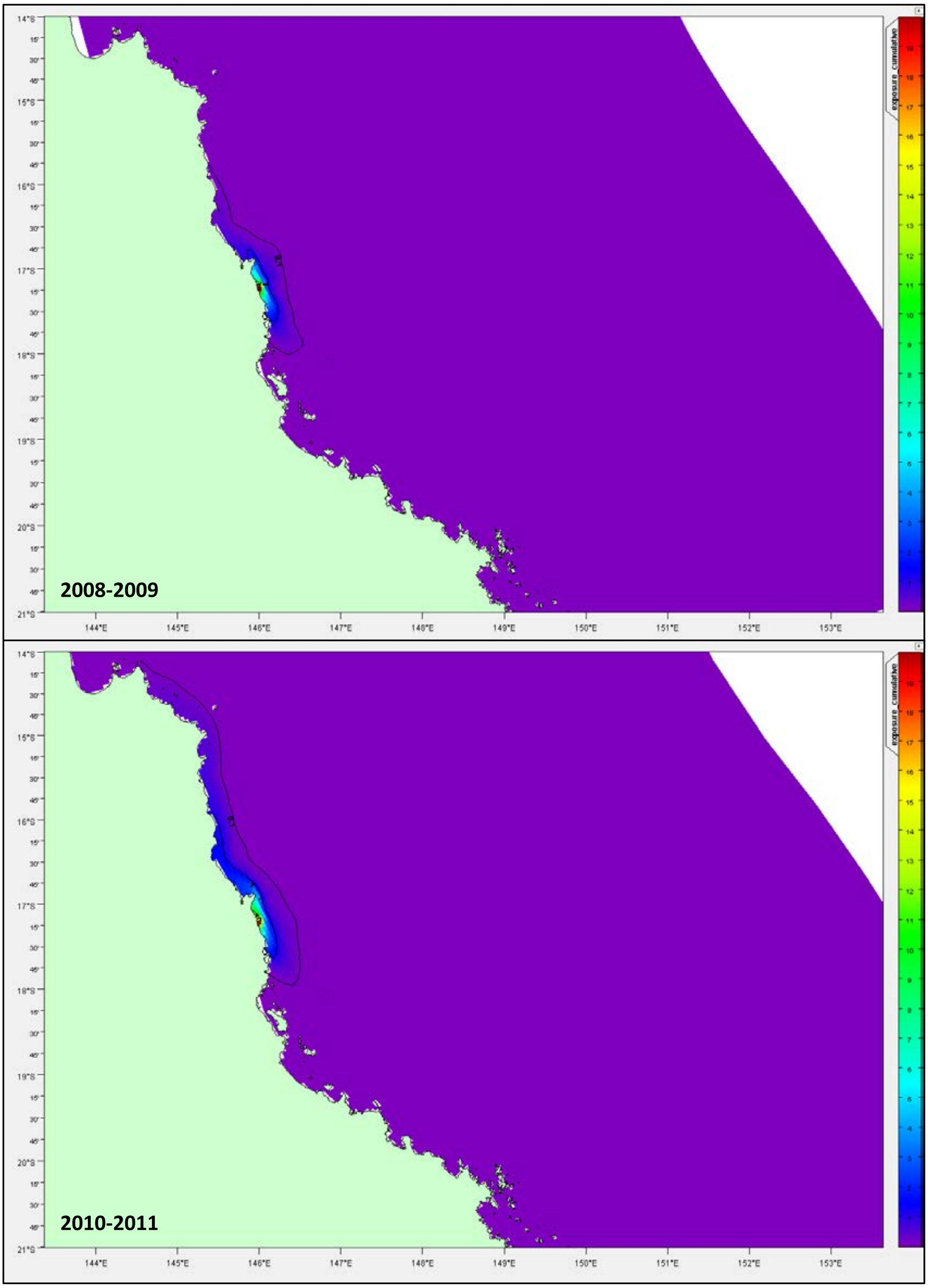

Figure 4 Cumulative exposure index for the Russell-Mulgrave River over the 2008-2009 (top) and 2010-2011 (bottom) wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposures are 45 and 47 at the river mouth for 2008-2009 and 2010-2011, respectively. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

Freshwater contributions of individual rivers to COTS outbreak initiation region

Simulated spatial footprints of river discharge exposure for the modelled rivers indicate that all rivers, apart from the Normanby River, produced plumes with spatial footprints that cover significant areas of the Cairns – Lizard Island region (exposure levels > 0.1). Recalling that the threshold concentration was set at 1%, an exposure index of 0.1 indicates at least a 10-day exposure to a tracer concentration of 0.01 x the discharge level; or shorter exposures to higher concentrations. The Burdekin River has an influence zone extending beyond Cairns to at least 16°S (Undine Reef), although the greatest exposure occurs between the river mouth and the Hinchinbrook Island (18°S), well south of the COTS initiation region. The Herbert River zone of influence is primarily limited to the region between Hinchinbrook Island and Cape Grafton. Discharge plumes from the Tully, Johnstone and Russell-Mulgrave Rivers all influence the lagoon north of Cairns, with diluted plumes extending north of Undine Reef. The smaller discharge of the Barron River (annual mean ca. 0.8 km^3) largely remains in the vicinity of Cairns, while the Daintree River influences a region extending from Low Isles to beyond Cape Melville (14.5°S). Freshwater from the Normanby River does not influence the shelf region south of Cape Melville. There is also significant variability in the extent of exposure between years, due to the response of dispersion dynamics to inter-annual variability in river flows (Figure 5) and prevailing weather and oceanographic conditions.

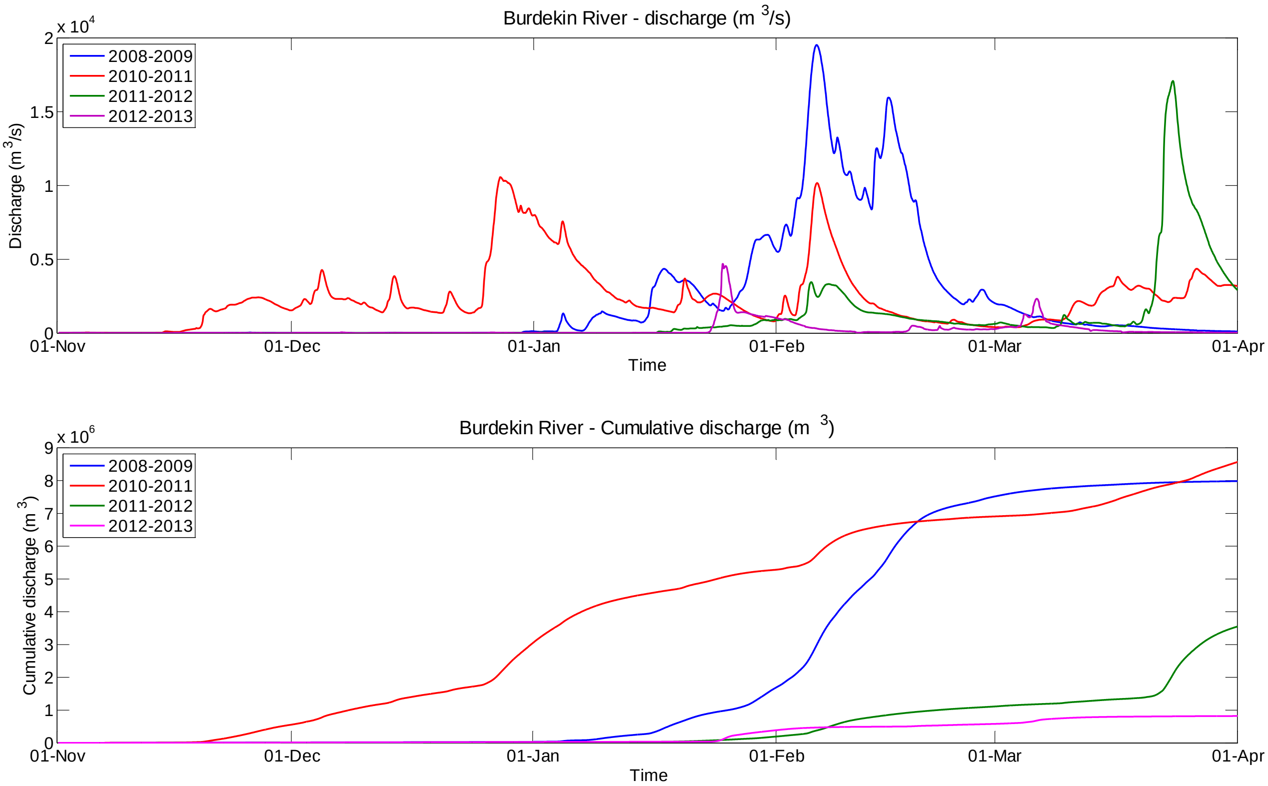

Figure 5 Daily (top) and cumulative (bottom) discharge from the Burdekin River for the 2008-2009, 2010-2011, 2011-2012 and 2012-2013 wet seasons. Note change in Y-axis scale between top and bottom plots.

Hydrodynamic modelling and analysis of passive tracer movements have been applied to assess the relative freshwater volumetric contributions of the major rivers impacting the Cairns – Lizard Island section of the GBR lagoon (Table 2). Rivers were ranked based on both their freshwater volumetric contribution to the entire Cairn-Lizard Island COTS outbreak region (14.5° – 17°S).

Table 2. Relative freshwater volumetric contributions of individual rivers to the COTS outbreak initiation region between Cairns (17°S) and Lizard Island (14.5°S). The relative contributions of individual rivers were normalized against the Daintree River, the largest river discharging directly into the outbreak initiation region. Ranking is based on magnitude of contribution, from 1 (highest) to 8 (lowest).

	Volumetric contribution noramilesd to Daintree				*Ranking* (1 highest contribution, 8 lowest)			
River	2008/09	2010/2011	2011/2012	2012/2013	2008/09	2010/2011	2011/2012	2012/2013
Normanby	0	0	0	0	6	8	8	8
Daintree	100	100	100	100	1	1	1	1
Barron	39	52	40	37	2	4	3	3
Russel Mulgrave	20	59	55	44	3	2	2	2
Johnstone	7	29	24	20	5	6	5	5
Tully	13	57	25	27	4	3	4	4
Herbert	0	7	0	0	6	7	6	7
Burdekin	0	47	0	0	6	5	7	6

Because of its central location (ca. 16°S) and significant runoff volume (annual mean ~ 1.3 Km^3), the Daintree River has the largest direct influence (discharge volume x duration [days] = Conc.Days) on the Cairns – Lizard Island region, followed in most cases in decreasing order by the Russell-Mulgrave, Barron, Tully and Rivers. The Normanby River generally flows north of Cape Melville and has little impact. The influence of the Burdekin is variable. The 2008-2009 and 2010-2011 wet season flows from the Burdekin were of similar magnitude (~29,000 GL and ~35,000 GL, respectively), however, during 2008-2009 the Burdekin plume had a significant southerly trajectory, before mixing across the shelf, limiting its northward propagation. During 2010-2011, the Burdekin plume remained close to the coast and travelled beyond Cape Grafton.

DIN contributions of individual rivers to COTS outbreak initiation region

Estimated volumetric contributions (Table 2) were combined with estimated DIN concentrations to assess and rank the DIN exposure contributions from the major rivers (Table 3). A risk score was calculated for each river, for each year, and rivers were ranked according to their DIN risk score.

Table 3 Relative contributions of freshwater and DIN Risk score and ranking for individual rivers influencing the COTS outbreak initiation region between Cairns (17°S) and Lizard Island (14.5°S). DIN risk is based on event mean concentrations of river DIN (Lewis et al., 2014).

2008-2009	FW Contribution (%) normalised to Daintree	Volumetric Ranking	FW Volume from DERM (GL)	FW Volume normalised to Daintree	EMC DIN Conc (ug/L)	Risk Score (DIN x FW volume % contribution)	DIN Risk Score Ranking
Normanby	0	8	2,346	4.48	80	0.000	8
Daintree	100	1	524	1.00	84	0.084	6
Barron	52	2	773	1.48	51	0.039	7
Russel Mulgrave	25	3	1,801	3.44	172	0.149	4
Johnstone	15	5	2,945	5.62	321	0.270	3
Tully	16	4	3,597	6.86	126	0.136	5
Herbert	6	7	9,505	18.14	253	0.291	2
Burdekin	12	6	29,352	56.02	201	1.365	1

2010-2011

Normanby	0	8	5,965	3.59	80	0.000	8
Daintree	100	1	1,662	1.00	84	0.084	6
Barron	52	4	1,929	1.16	51	0.031	7
Russel Mulgrave	59	2	3,243	1.95	172	0.200	4
Johnstone	29	6	5,269	3.17	321	0.293	3
Tully	57	3	7,060	4.25	126	0.307	2
Herbert	7	7	11,447	6.89	253	0.121	5
Burdekin	47	5	34,839	20.97	201	1.994	1

2011-2012

Normanby	0	8	1,148	1.25	80	0.000	8
Daintree	100	1	918	1.00	84	0.084	4
Barron	40	3	775	0.84	51	0.017	5
Russel Mulgrave	55	2	2,330	2.54	172	0.242	2
Johnstone	24	5	2,949	3.21	321	0.252	1
Tully	25	4	3,618	3.94	126	0.123	3
Herbert	0	6	4,360	4.75	253	0.000	6
Burdekin	0	7	15,529	16.91	201	0.000	7

2012-2013

Normanby	0	8	1822	2.69	80	0.000	8
Daintree	100	1	677	1.00	84	0.084	4
Barron	37	3	282	0.42	51	0.008	5
Russel Mulgrave	44	2	1371	2.03	172	0.153	2
Johnstone	20	5	1904	2.81	321	0.177	1
Tully	27	4	2586	3.82	126	0.131	3
Herbert	0	7	2819	4.17	253	0.000	7
Burdekin	0	6	3355	4.96	201	0.001	6

Risk scores for each river were averaged across the 4 years of simulation to derive a mean risk, and the rivers were then Ranked accordingly. In addition, a separate ranking was determined based only on the 6 major rivers of the Wet Tropics region (Table 4).

Table 4 Summary of risk scores, mean risk and ranking based on mean risk for all rivers, and for the Wet Tropics sub-set of rivers.

	Risk score					**Ranking - based on mean**	
	2008/09	2010/11	2011/12	2012/13	Mean	All rivers	Wet tropics only
Normanby	0.00	0.00	0.00	0.00	0.00	8	
Daintree	0.08	0.08	0.08	0.08	0.08	6	5
Barron	0.04	0.03	0.02	0.01	0.02	7	6
Russel Mulgrave	0.15	0.20	0.24	0.15	0.19	3	2
Johnstone	0.27	0.29	0.25	0.18	0.25	2	1
Tully	0.14	0.31	0.12	0.13	0.17	4	3
Herbert	0.29	0.12	0.00	0.00	0.10	5	4
Burdekin	1.37	1.99	0.00	0.00	0.84	1	

Based on the Tropwater EMC river nutrient data set (Table 3 and Table 4), the greatest risk to the COTS outbreak initiation region was estimated to come from the Burdekin River during high flow years (2008-2009, 2010-2011), and the Johnstone River during lower flow conditions. For all years modelled, the Johnstone River ranks in the highest 3 DIN contributors (Table 3), and this is reflected in the ranking based on mean risk scores (Table 4) where the Johnstone River ranks second behind the Burdekin River when considering all rivers. When considering only the Wet Tropics rivers (e.g. Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers) the Johnstone is estimated to present the largest risk of contributing to the DIN pool in the COTS outbreak region. The high level of DIN risk from the Johnstone River is related to the large volume discharged (mean = 3.2 km^3 over the 4 years of simulation) and but also due to the high estimated concentration of DIN in the discharge (321 µg N L^{-1}). The Russell-Mulgrave and Tully Rivers rank consecutively lower than the Johnstone River for DIN risk, however the mean risk values for these three rivers are similar. The similarity in risk scores, particularly between the Russel-Mulgrave and Tully Rivers is interesting due to their different loads and discharge characteristics. Event mean DIN concentration for the Tully River are <50% of the mean EMC for the Wet Tropics rivers (mean = 168 µg N L^{-1}), but the Tully River discharge is consistently higher than that in the Johnstone and Russell-Mulgrave Rivers. Conversely, the Russell-Mulgrave River has a discharge that is, on average (over the 4 season modelled), approximately half that of the Tully River, although the Russell-Mulgrave DIN loads are ~35% greater than the load from the Tully River.

4 Conclusions.

Hydrodynamic modelling has been applied to rank the influence of individual rivers with discharges that affect the Cairns – Lizard Island region of the GBR for four recent wet seasons (2008-09, 2010-11, 2011-12, 2012-13) that have preceded the current incipient COTS outbreak. Riverine inputs were ranked using both their volumetric influence and a DIN Risk score that combined volumetric inputs with DIN loads. Rankings based on volumetric contributions were generally consistent between years, with the Daintree dominating freshwater delivery into the region, typically followed in ranking by the Russell-Mulgrave, Tully and Barron Rivers. Rankings based on DIN Risk scores showed that Johnstone, Russell-Mulgrave, Tully, and Burdekin Rivers are the dominant rivers contributing to the DIN pool in the outbreak region. Together these rivers contributed >85% of the total DIN input to the region, based on mean DIN contributions over the 4 years modelled.

If the Burdekin and Normanby rivers are excluded from the analysis and only Wet Tropics rivers are considered, the Johnstone River is shown to be the largest contributor of DIN to the COTS outbreak region, with the Russell-Mulgrave and Tully Rivers ranking consecutively lower. When comparing discharges and volumetric contributions to the outbreak region from these three Rivers, the Russell-Mulgrave consistently out ranks the Tully and Johnstone Rivers (in that order), however, when combined with DIN load data, the mean risk values for the Russell-Mulgrave, Tully and Johnstone Rivers are similar. This indicates that for these rivers, it is the DIN load rather than discharge that is the primary determinant of the DIN risk score for these rivers.

5 References

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Appendix 1

Exposure maps for river between the Burdekin and Daintree rivers for 2008-09, 2010-11, 2011-12, 2012-13 wet seasons.

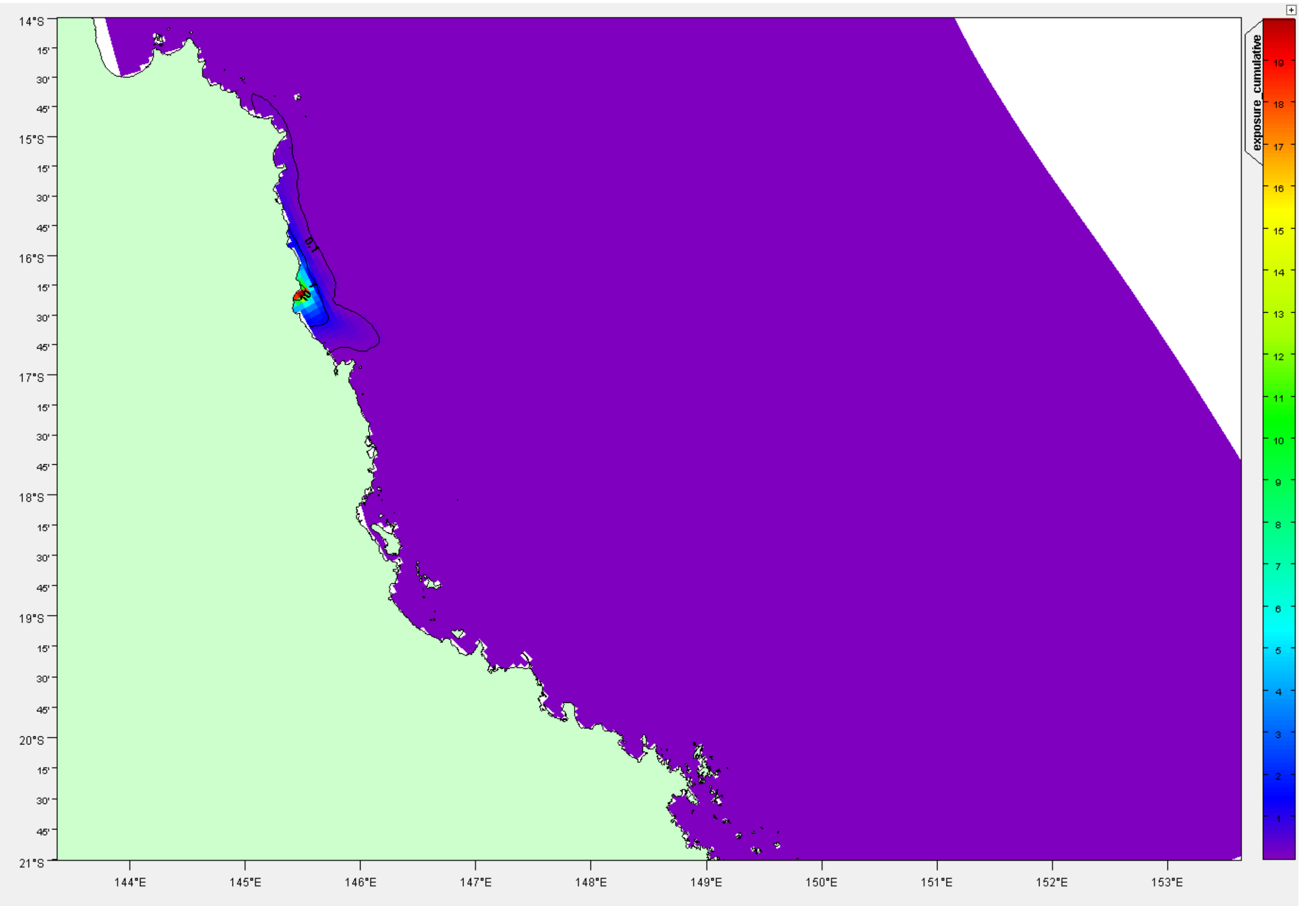

Figure A.1 Cumulative exposure index for the Daintree River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 39 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

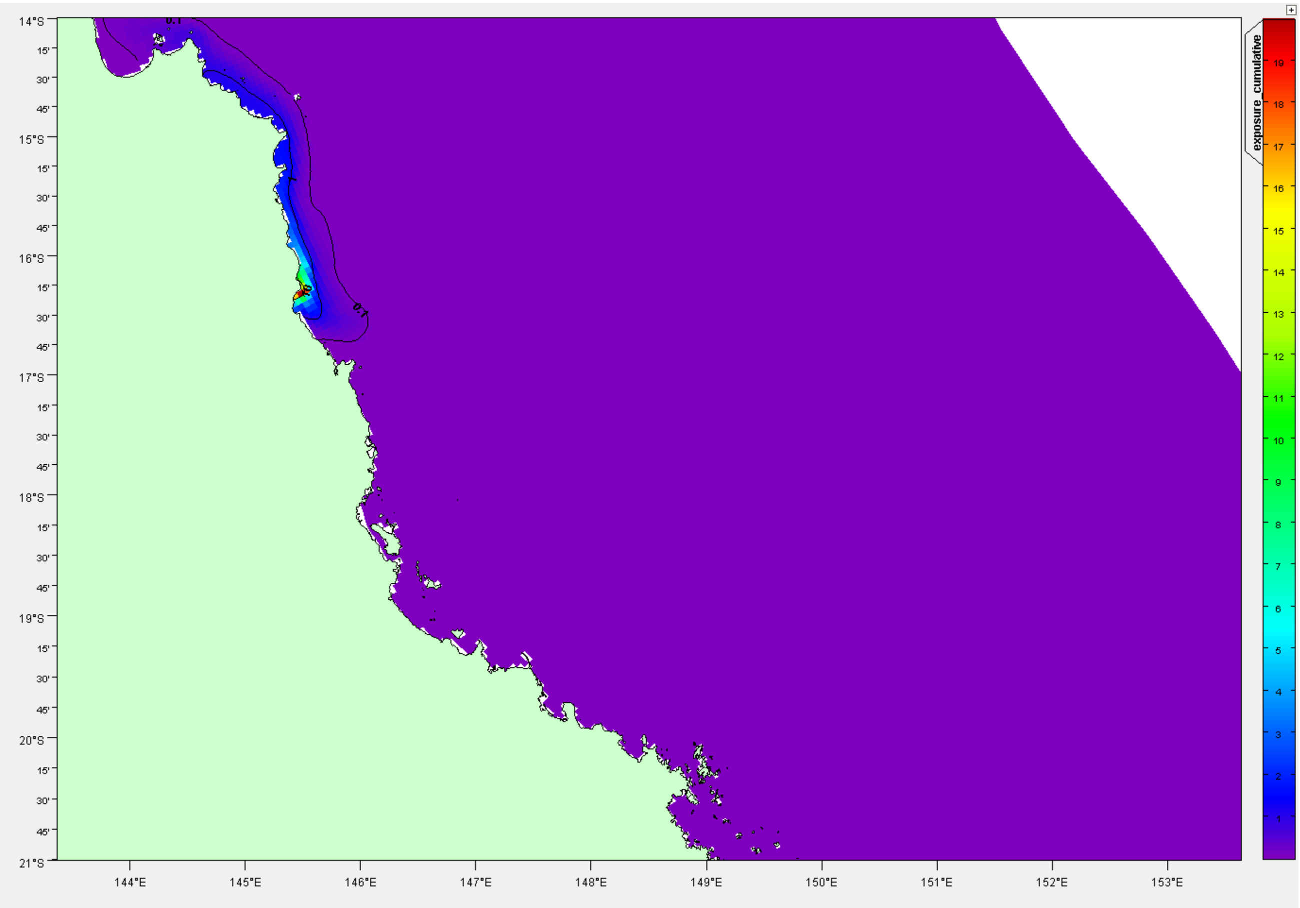

Figure A.2 Cumulative exposure index for the Daintree River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 39 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

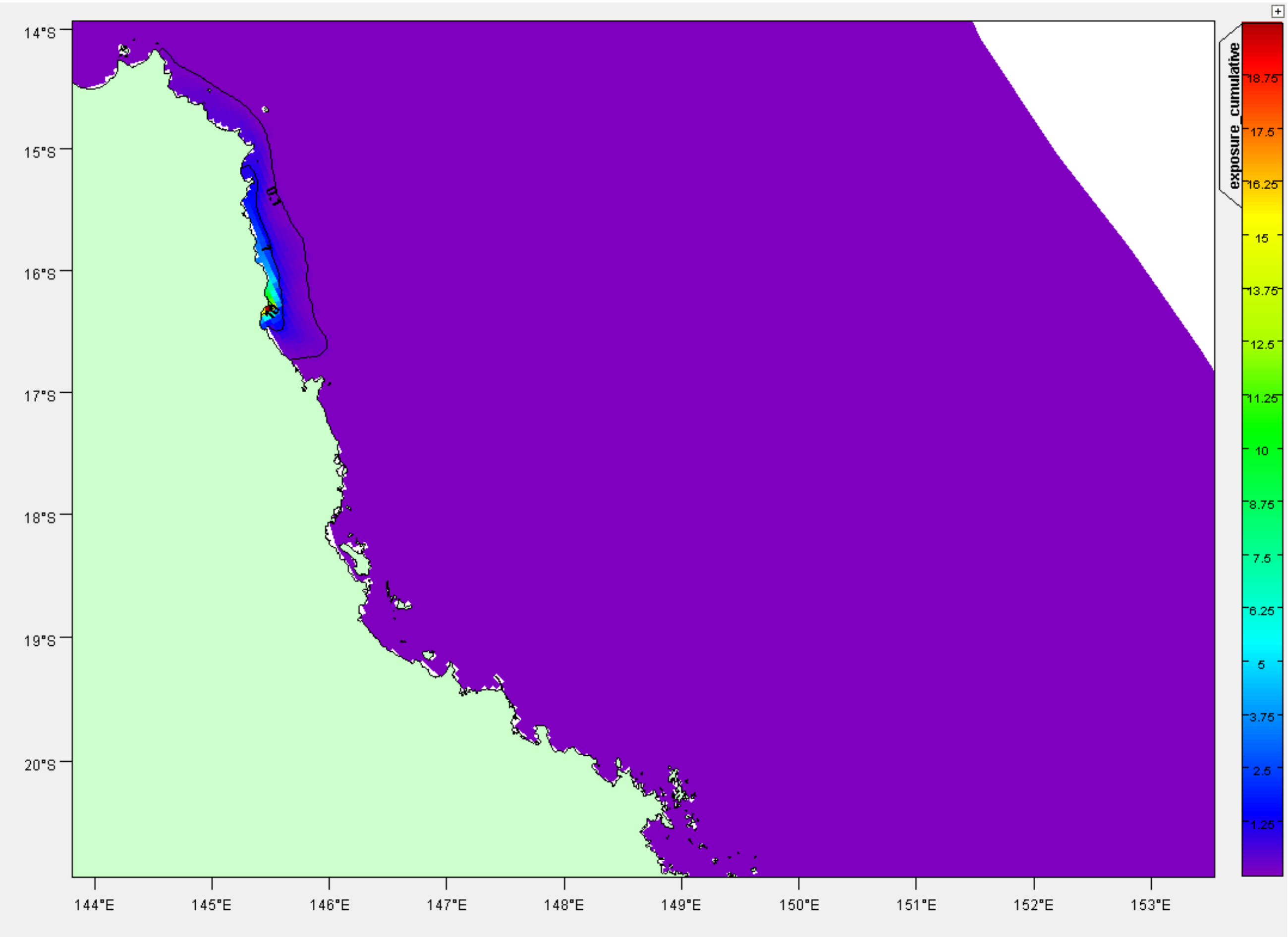

Figure A.3 Cumulative exposure index for the Daintree River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 33 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

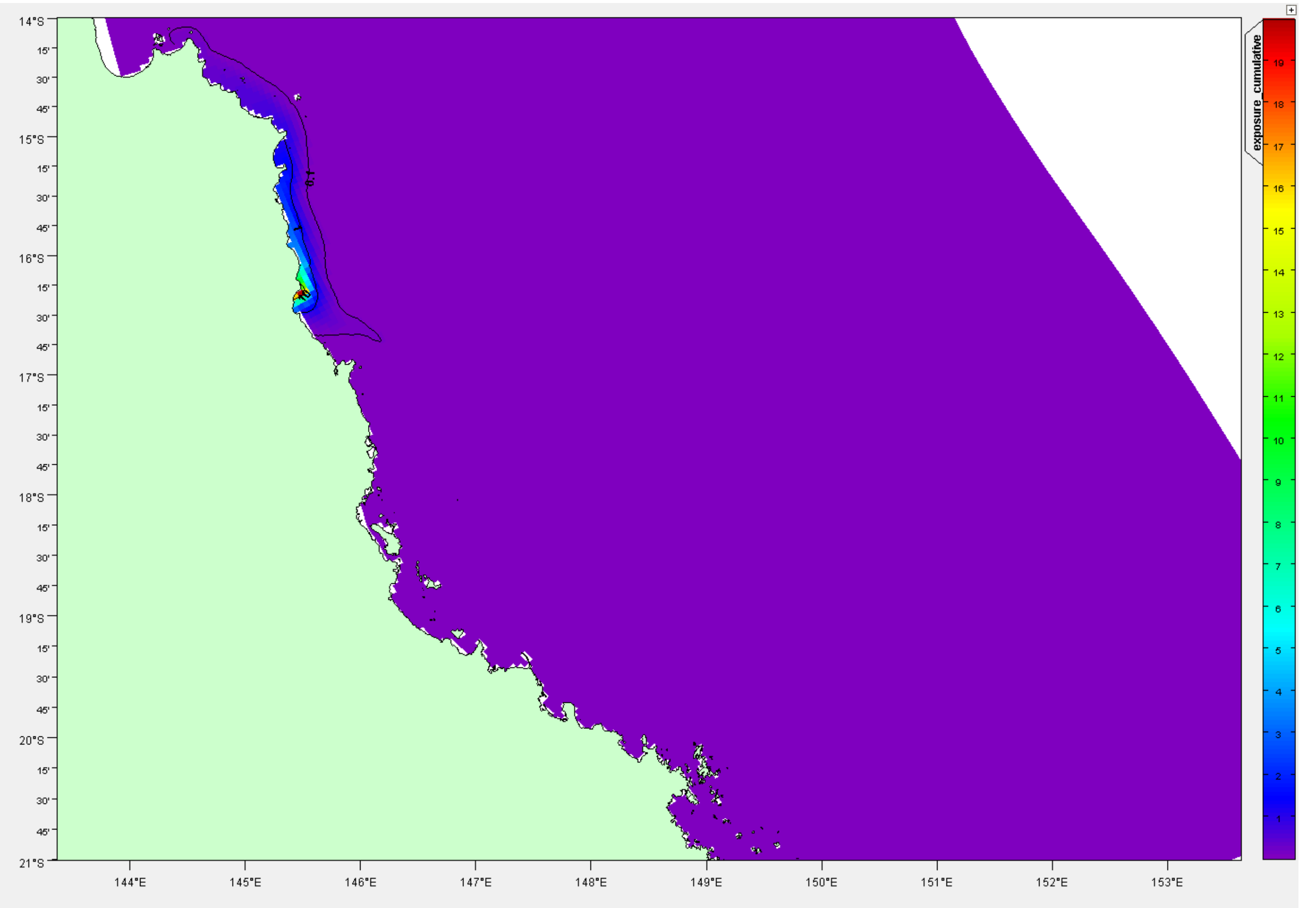

Figure A.4 Cumulative exposure index for the Daintree River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 32 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

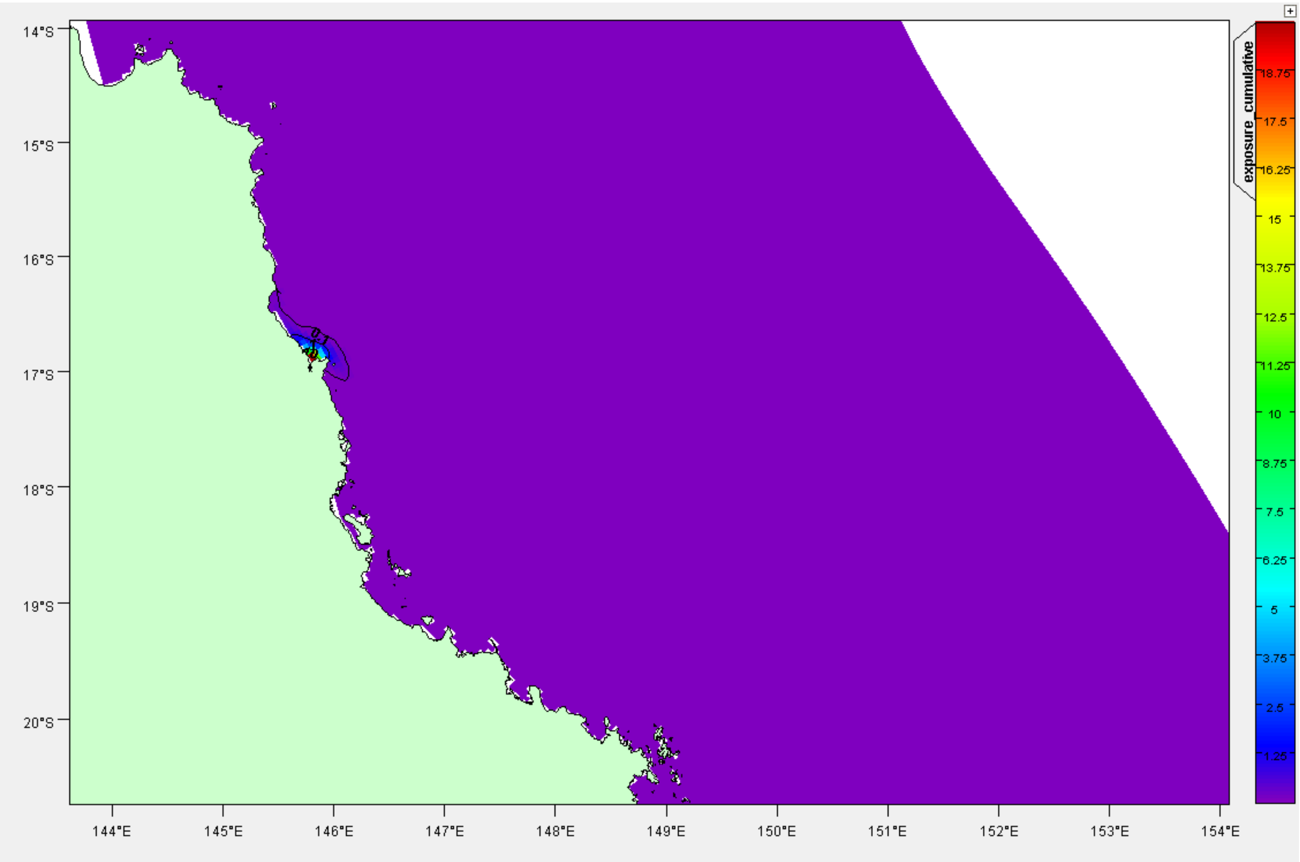

Figure A.5 Cumulative exposure index for the Barron River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 49 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

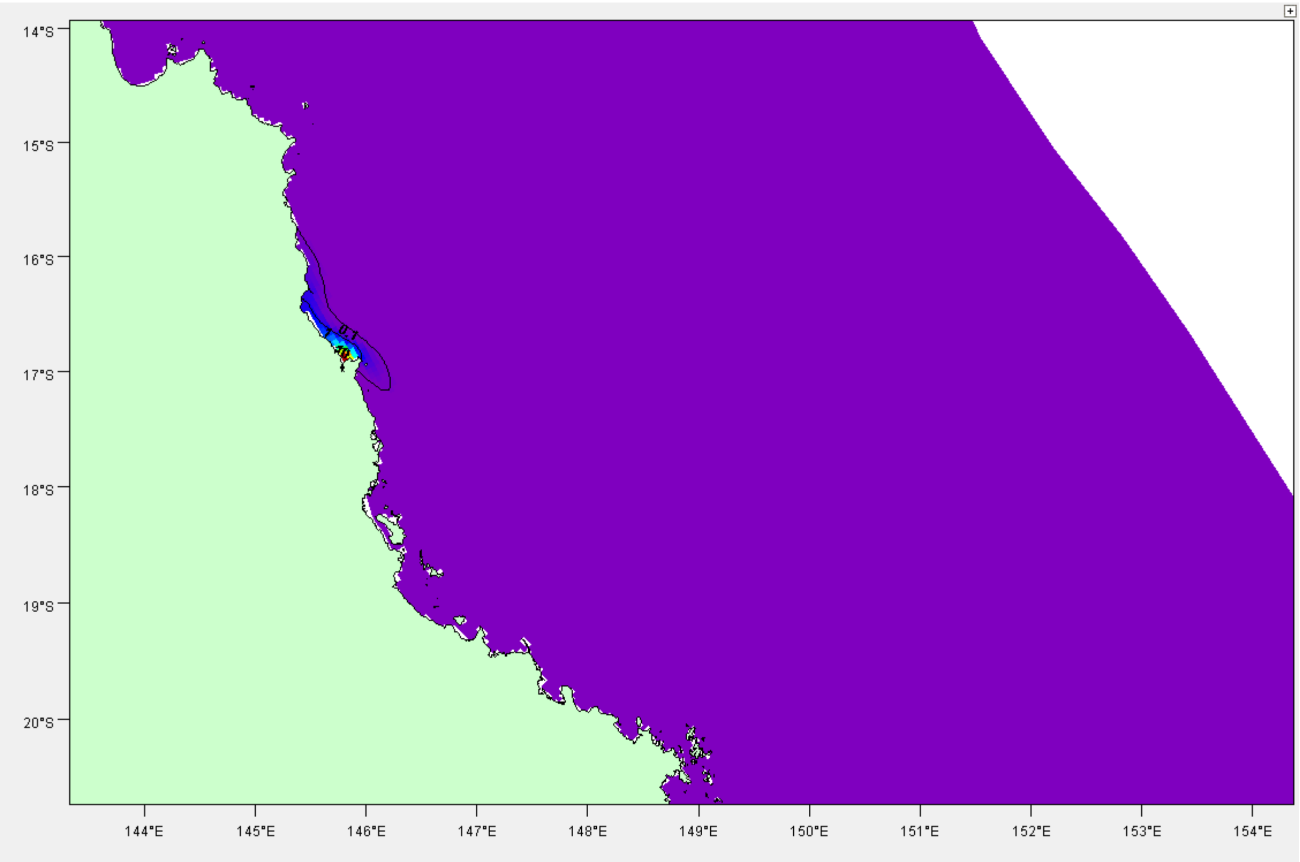

Figure A.6 Cumulative exposure index for the Barron River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 58 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

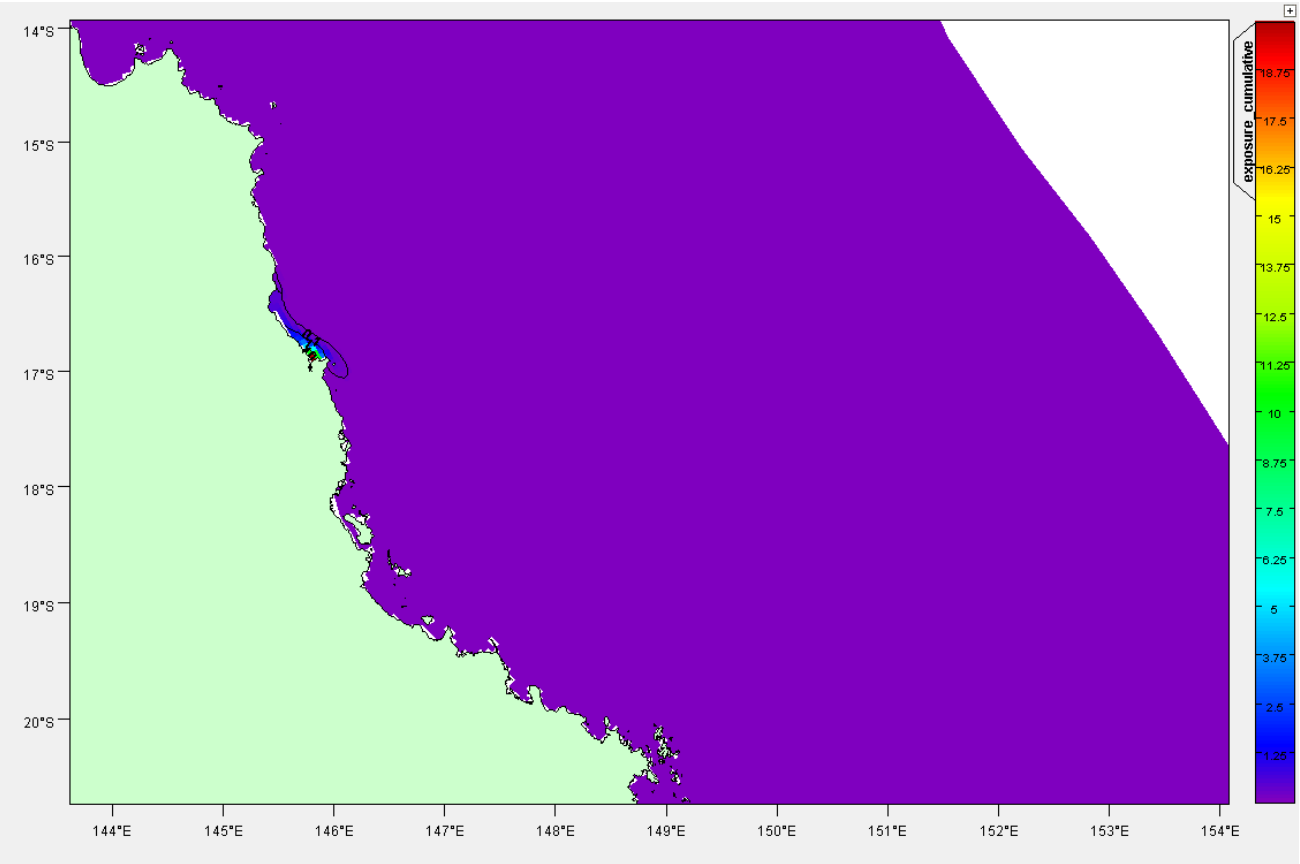

Figure A.7 Cumulative exposure index for the Barron River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 45 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

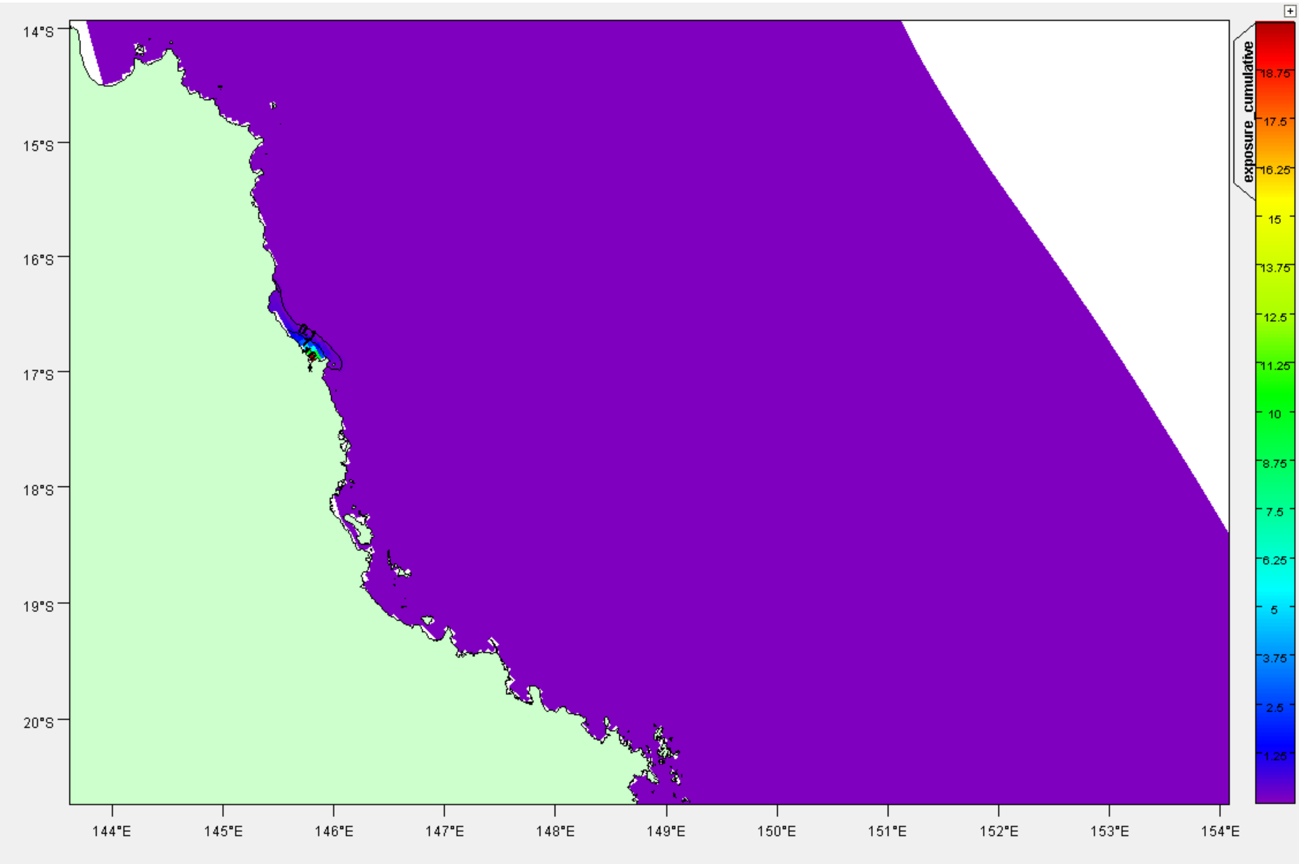

Figure A.8 Cumulative exposure index for the Barron River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 43 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

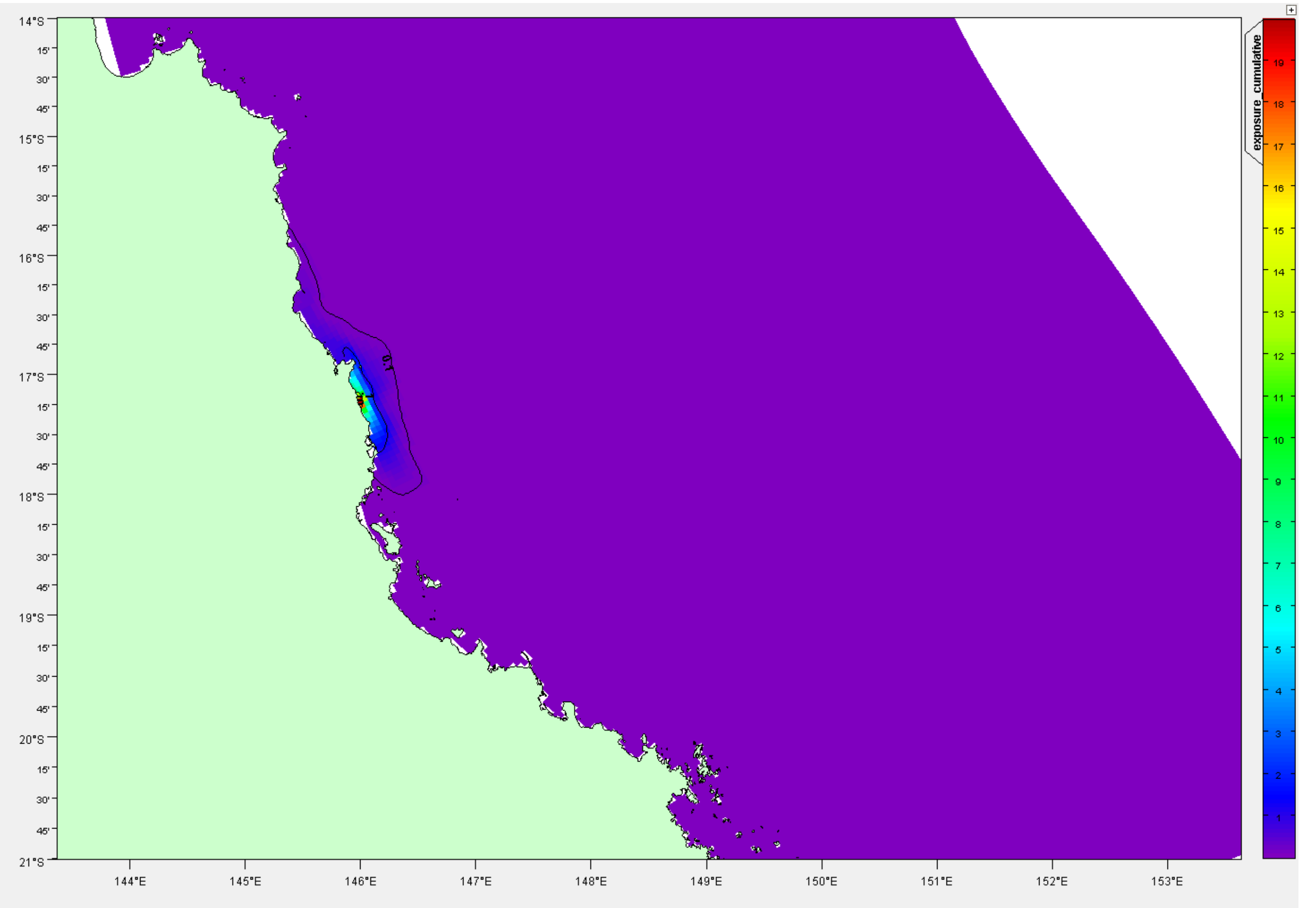

Figure A.9 Cumulative exposure index for the Russell-Mulgrave River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 45 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

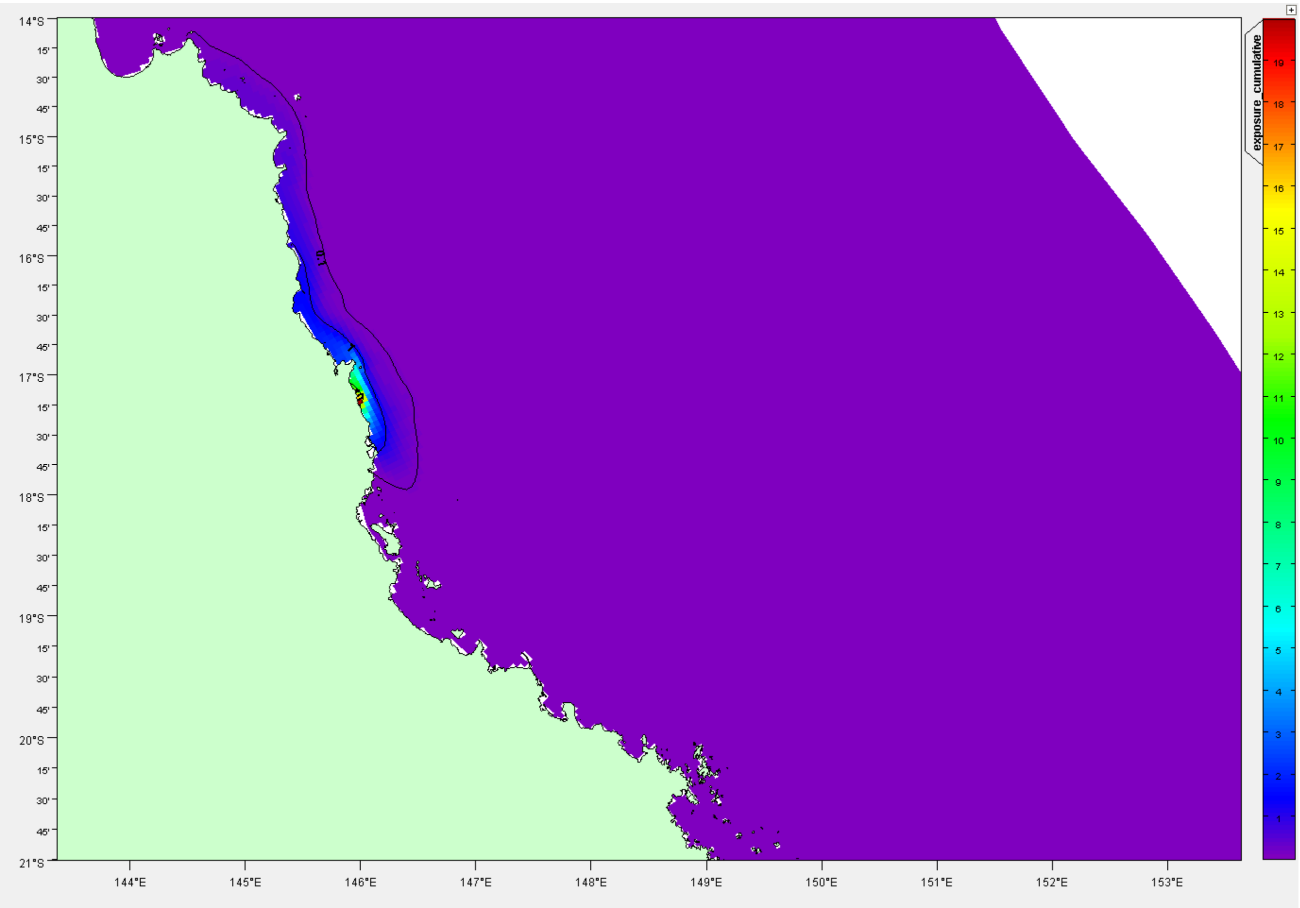

Figure A.10 Cumulative exposure index for the Russell-Mulgrave River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 47 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

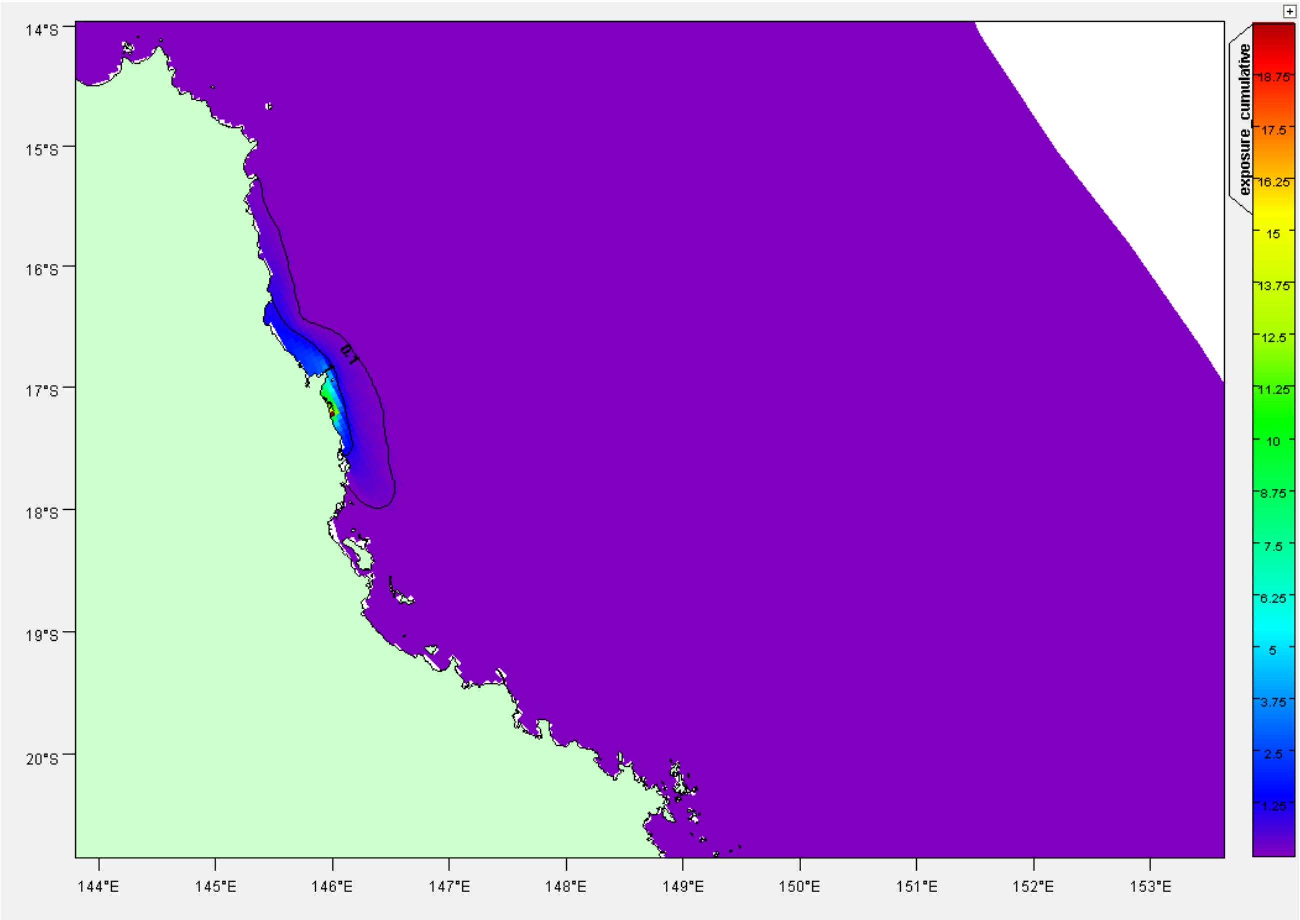

Figure A.11 Cumulative exposure index for the Russell-Mulgrave River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 43 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

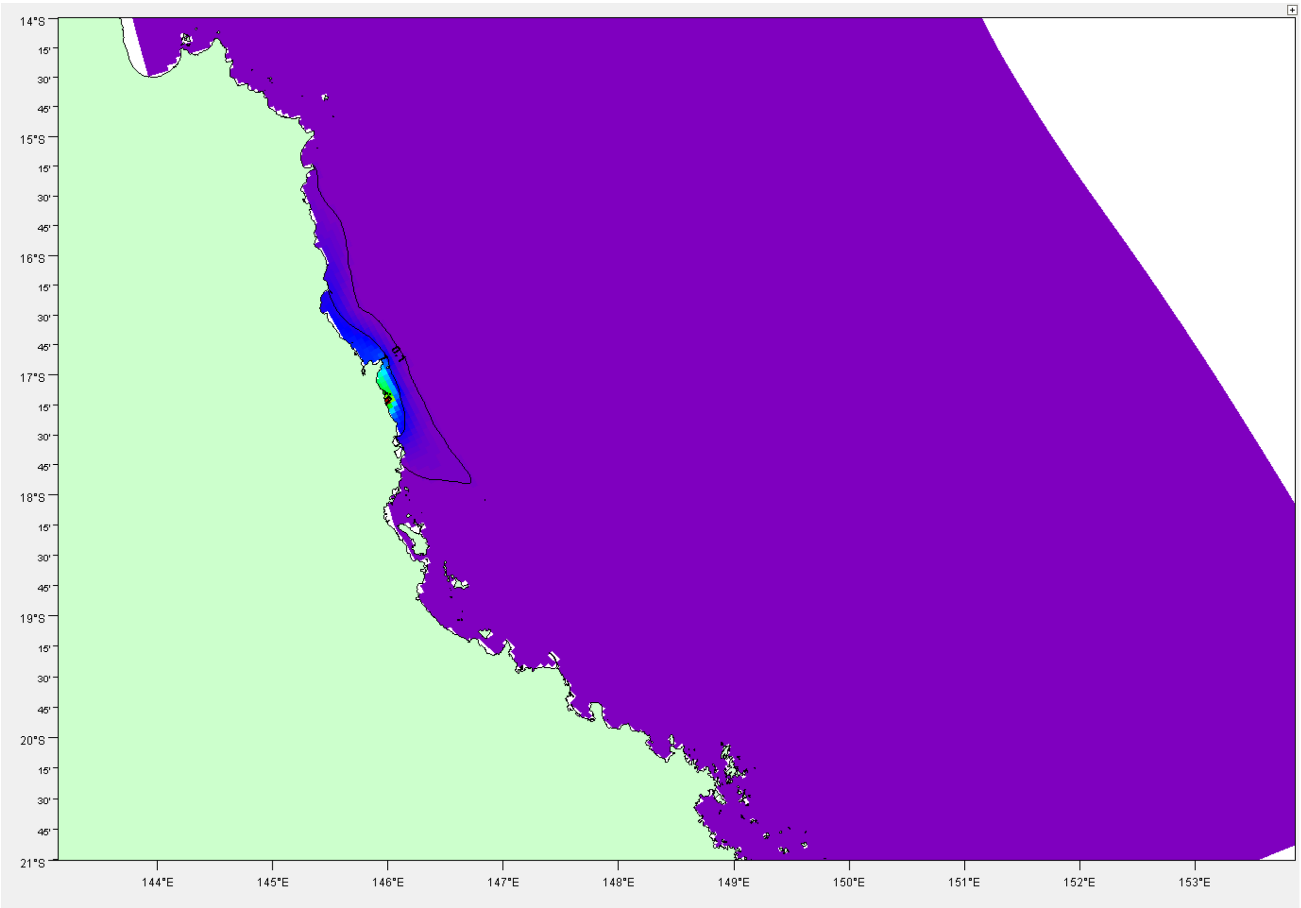

Figure A.12 Cumulative exposure index for the Russell-Mulgrave River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 41 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

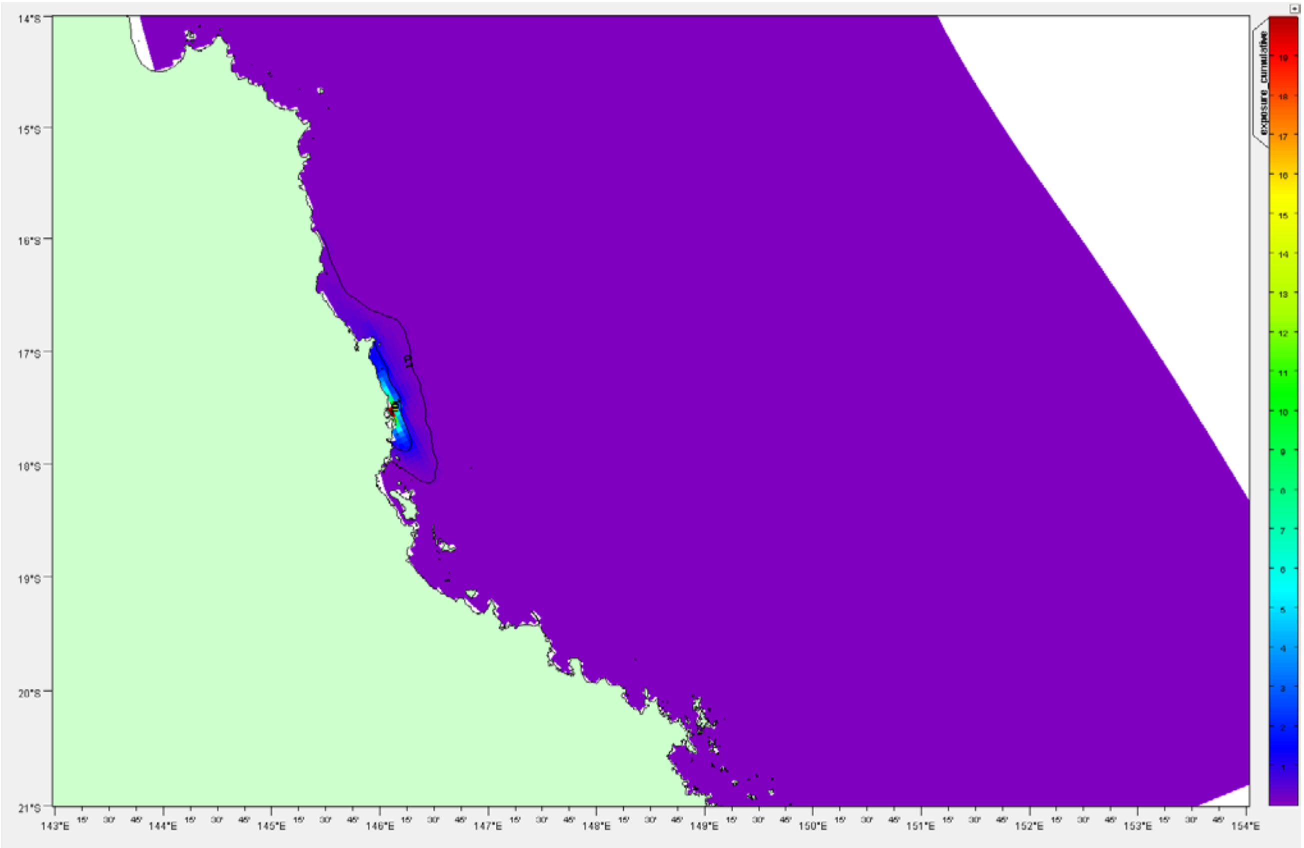

Figure A.13 Cumulative exposure index for the Johnstone River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 51 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

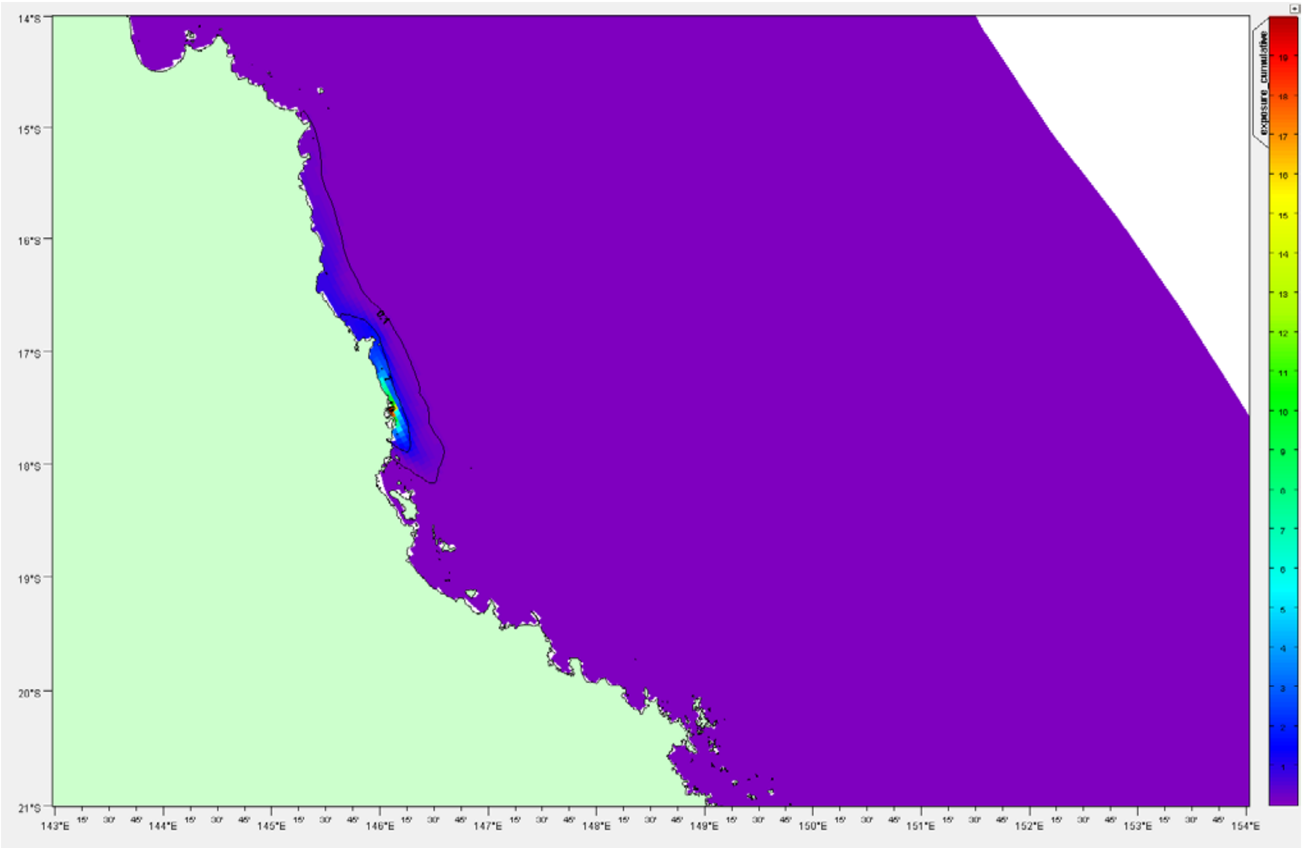

Figure A.14 Cumulative exposure index for the Johnstone River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 54 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

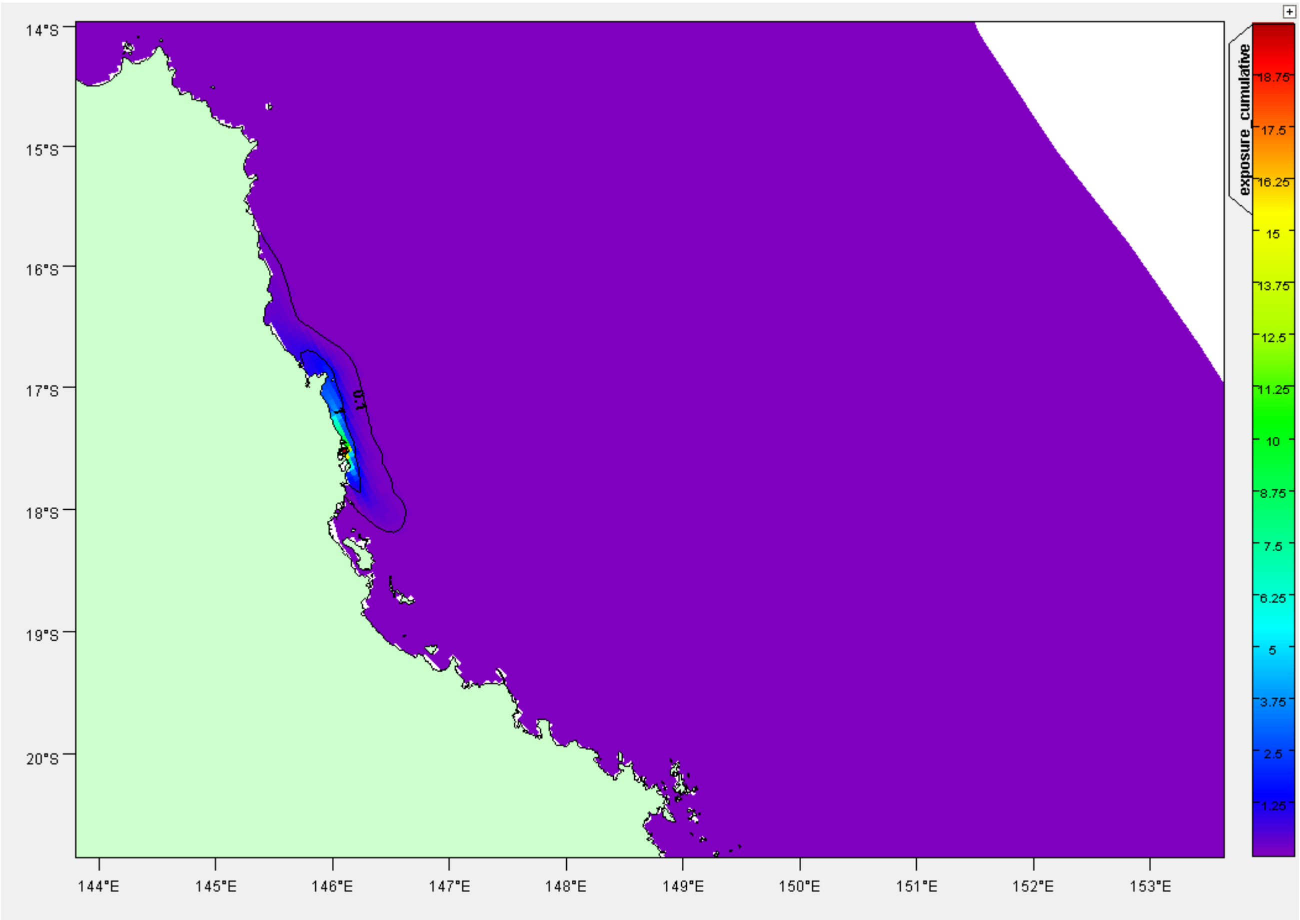

Figure A.15 Cumulative exposure index for the Johnstone River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 48 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

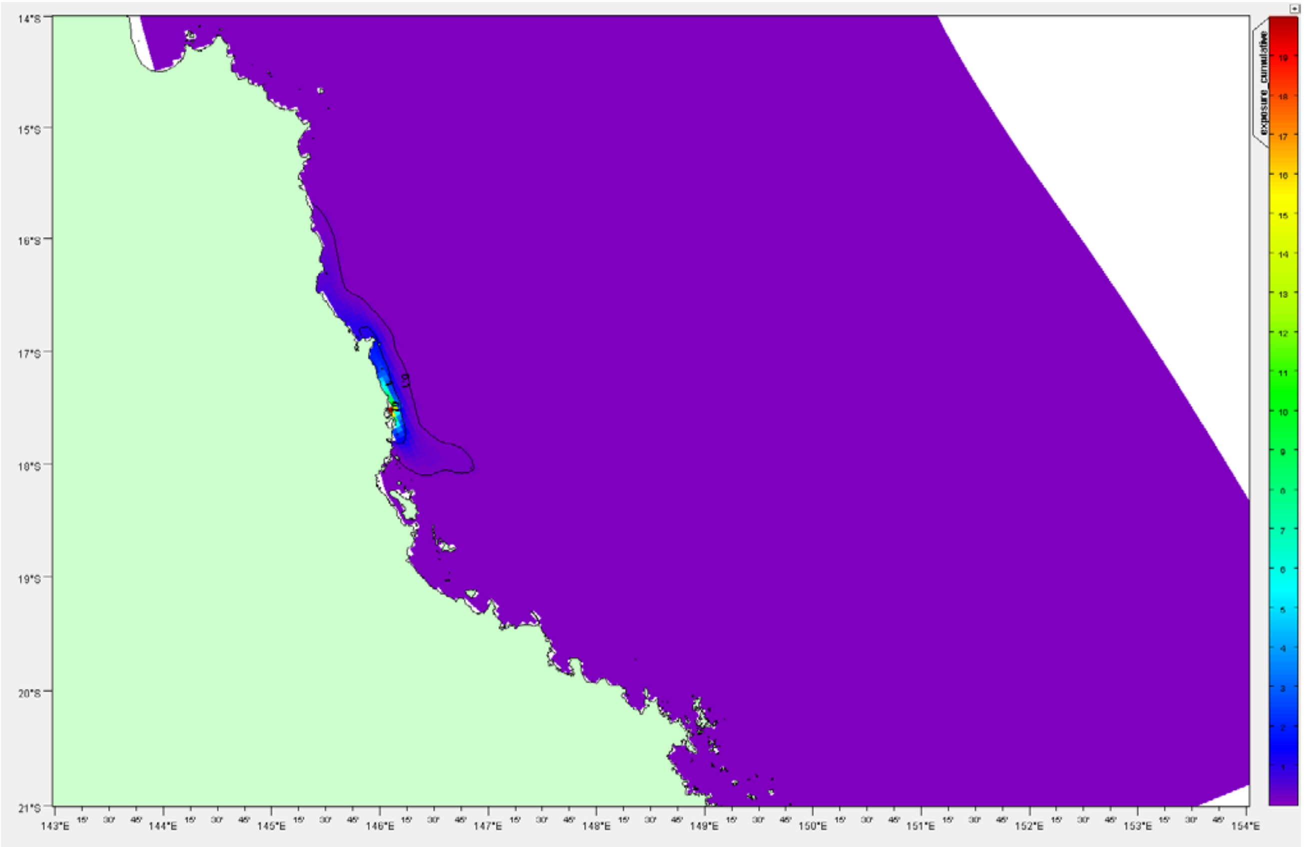

Figure A.16 Cumulative exposure index for the Johnstone River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 46 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

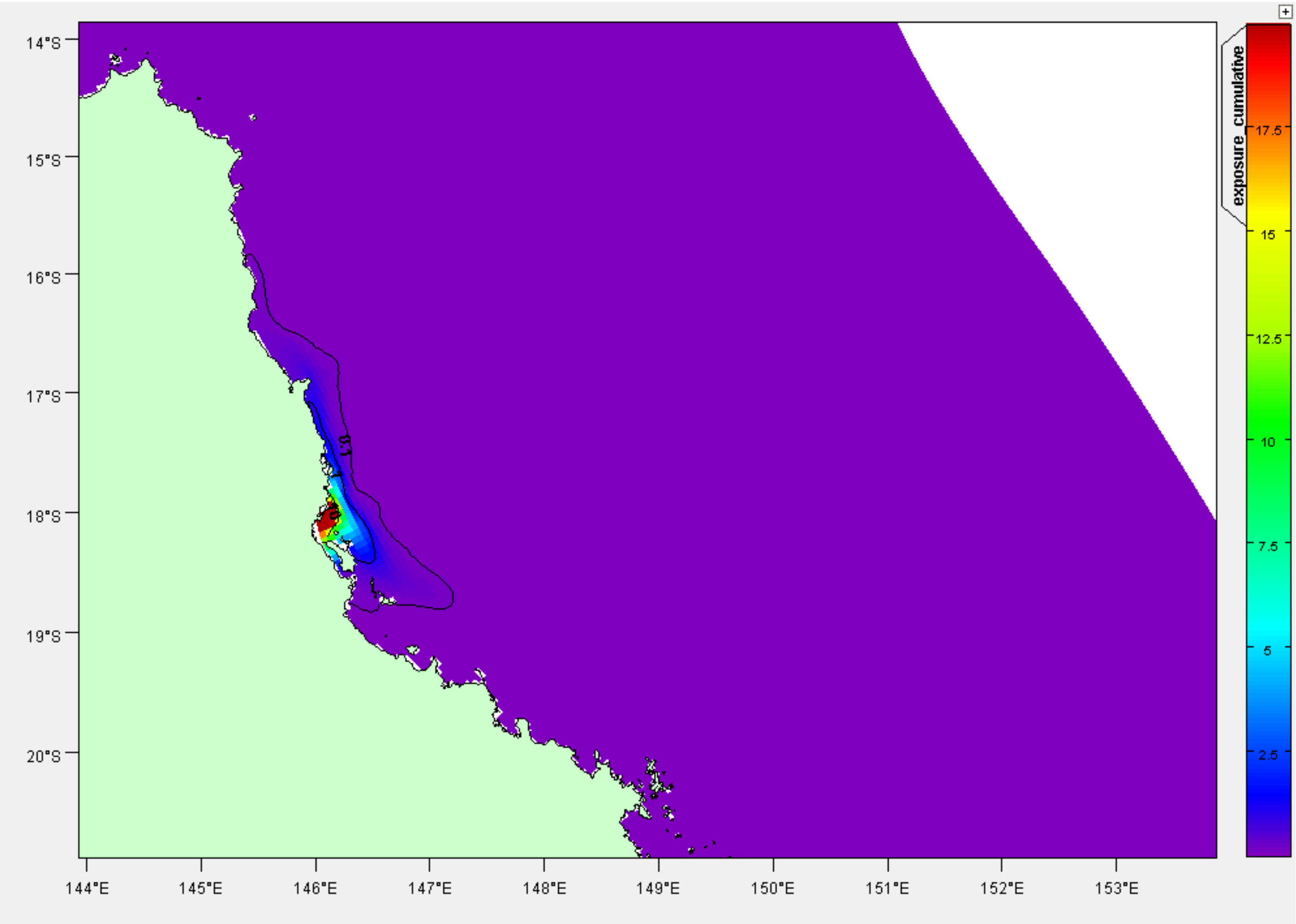

Figure A.17 Cumulative exposure index for the Tully River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 103 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

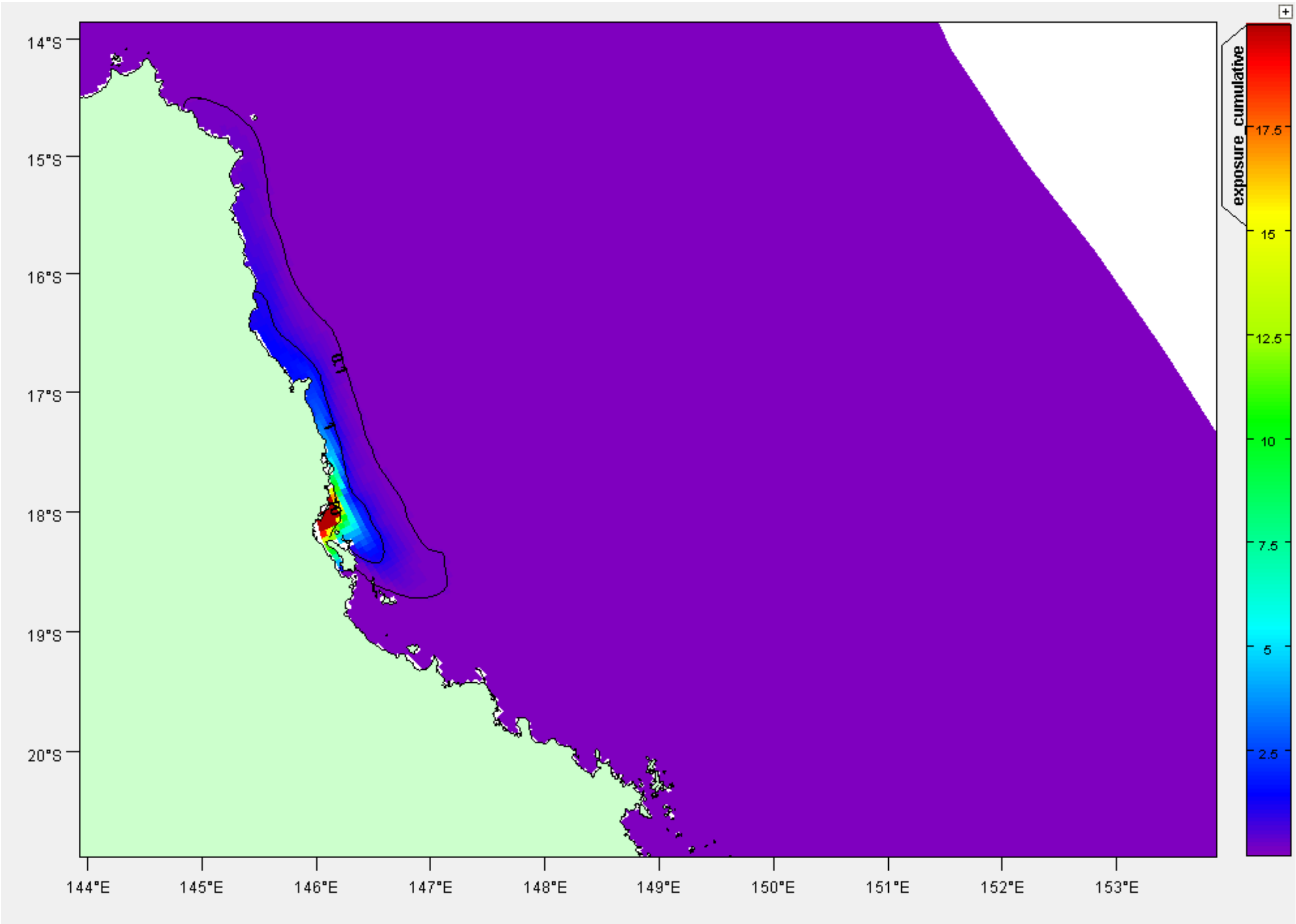

Figure A.18 Cumulative exposure index for the Tully River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 110 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

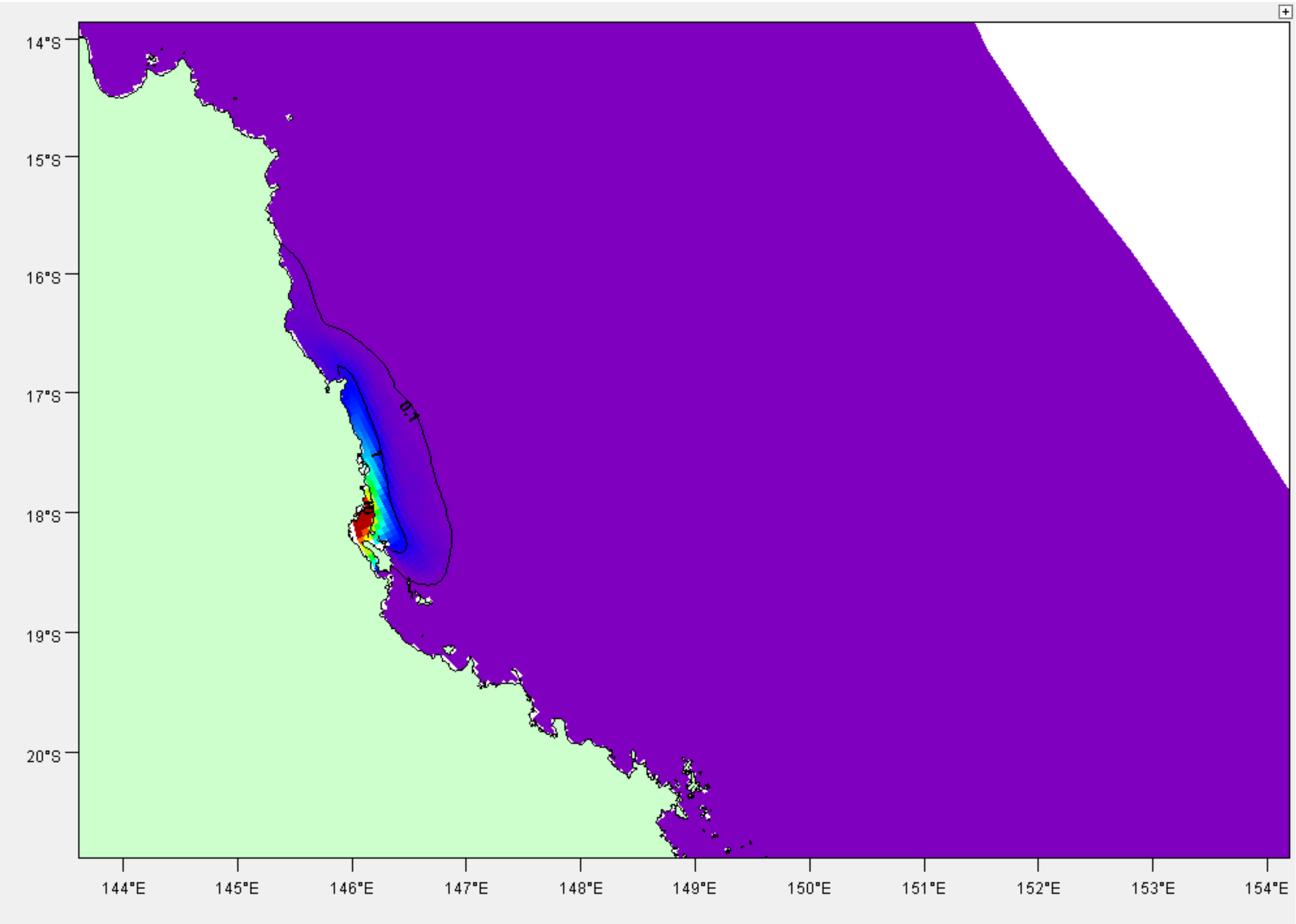

Figure A.19 Cumulative exposure index for the Tully River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 91 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

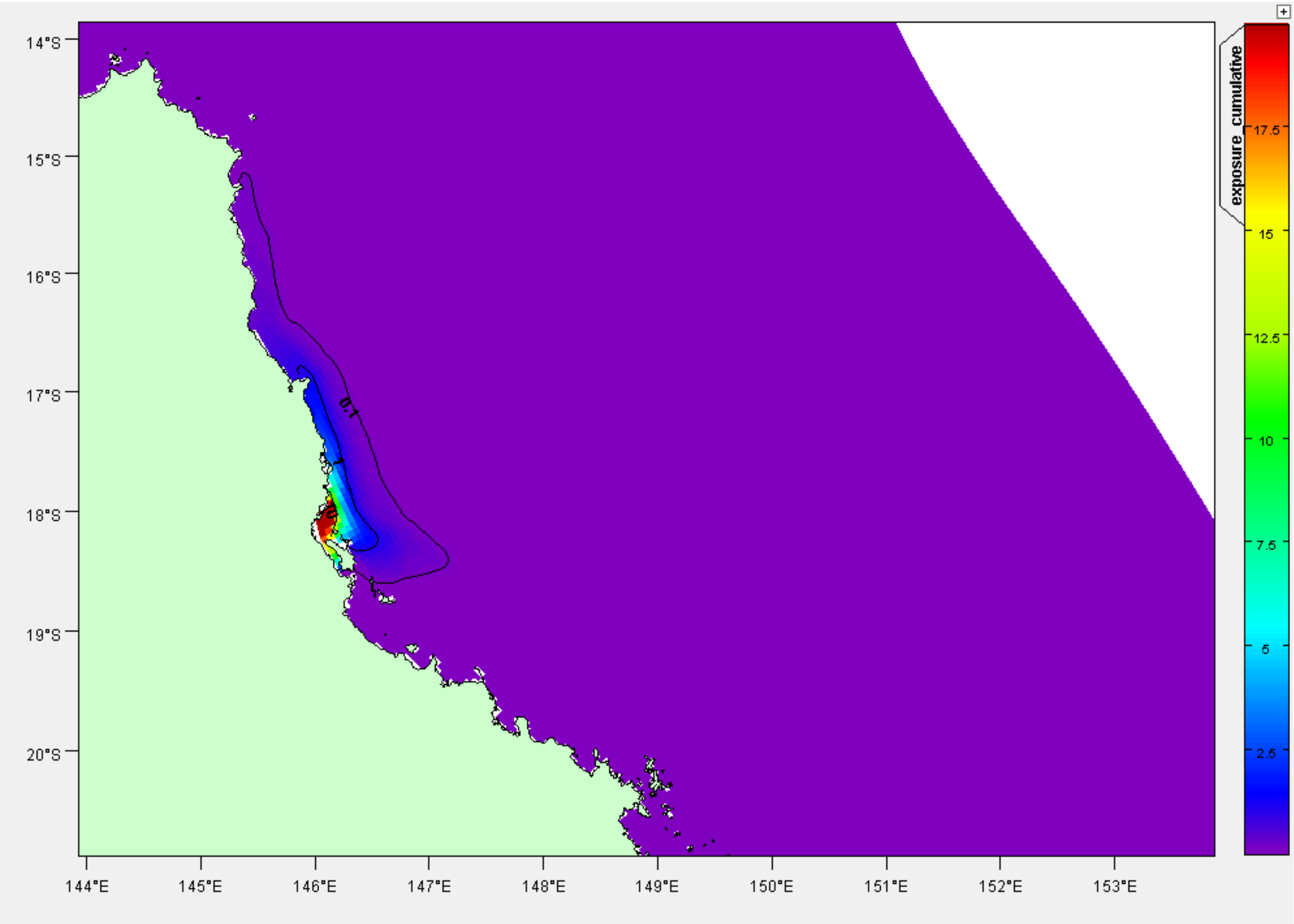

Figure A.20 Cumulative exposure index for the Tully River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 81 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

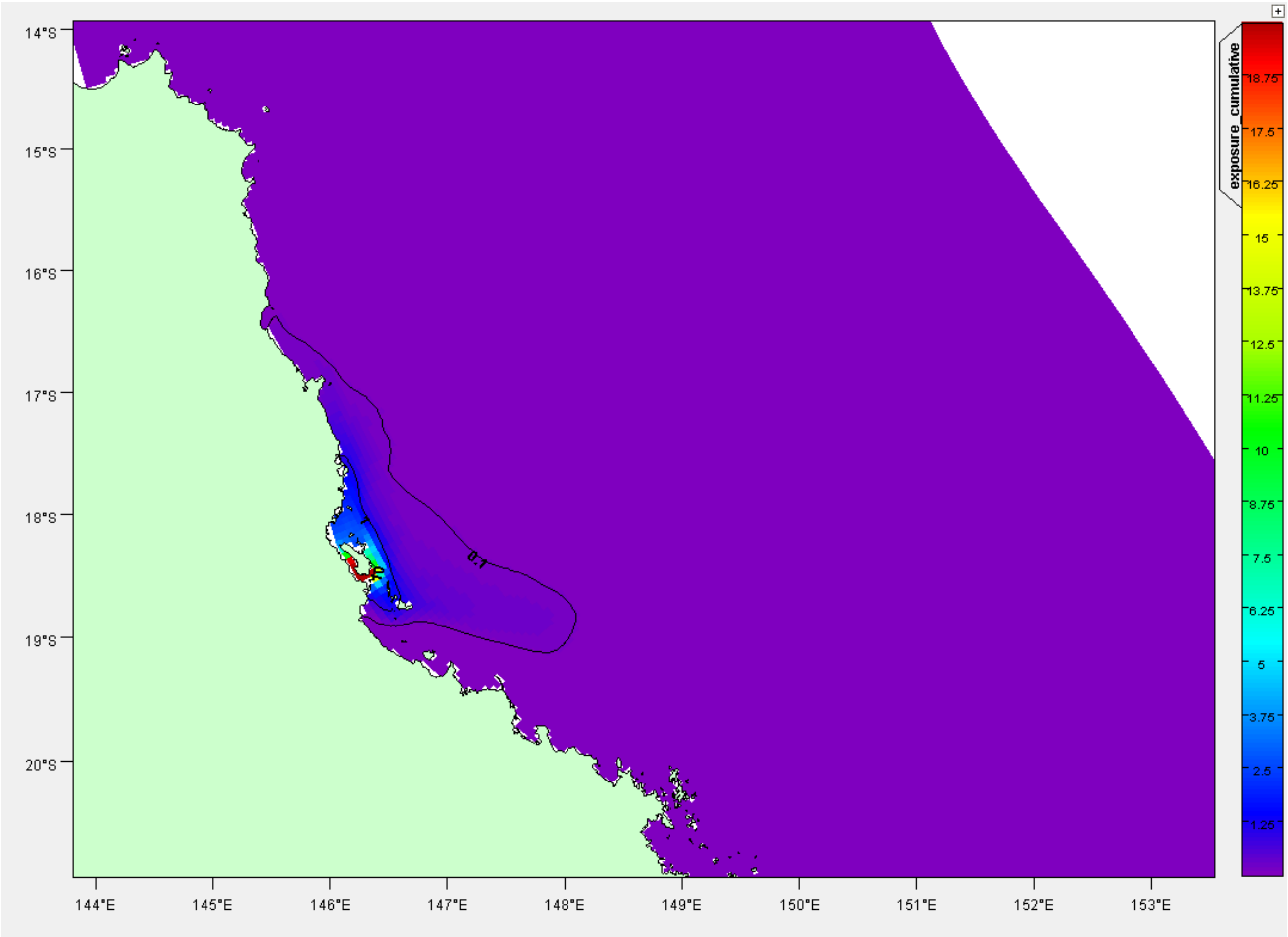

Figure A.21 Cumulative exposure index for the Herbert River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 84 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

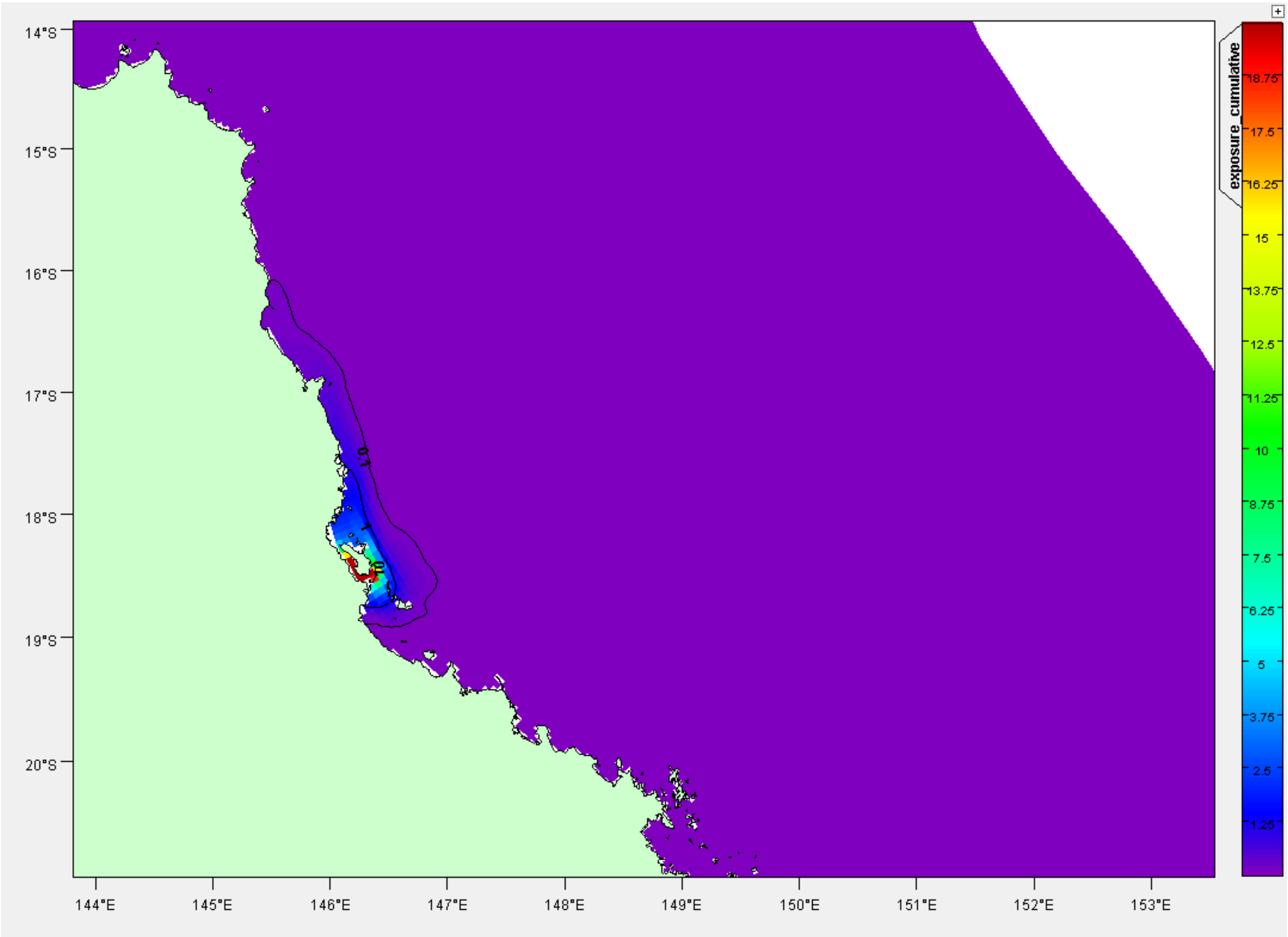

Figure A.22 Cumulative exposure index for the Herbert River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 92 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

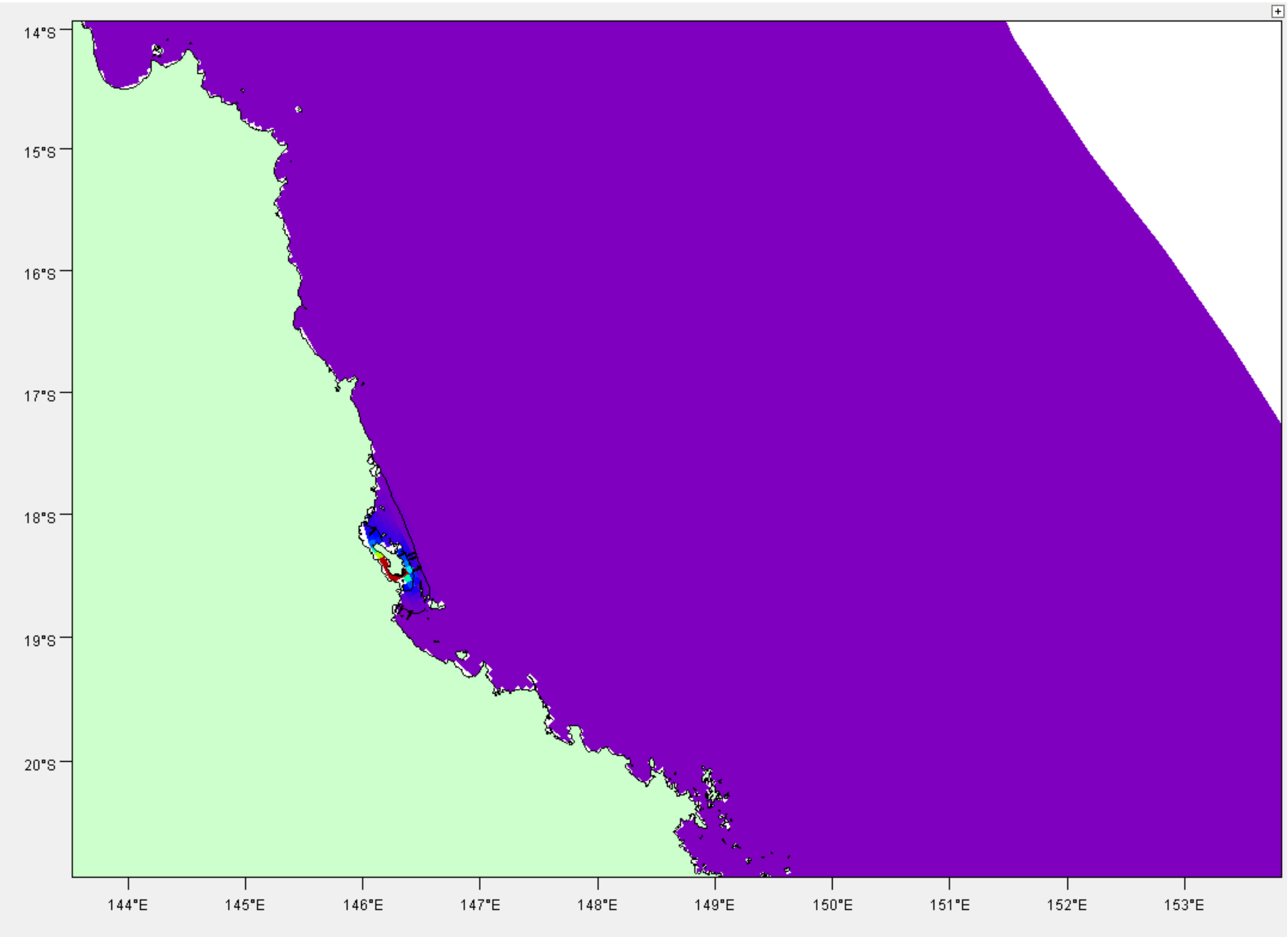

Figure A.23 Cumulative exposure index for the Herbert River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 69 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

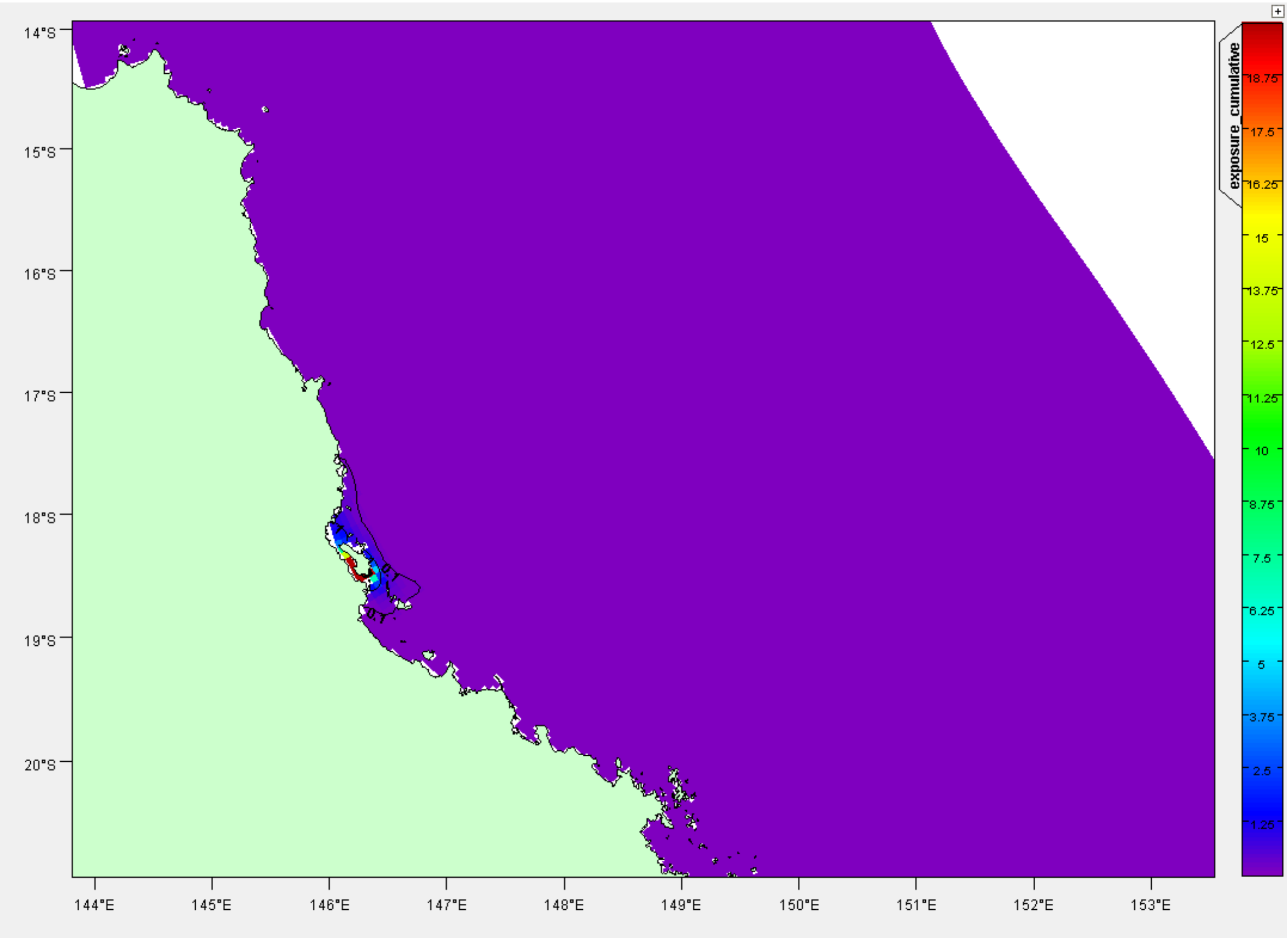

Figure A.24 Cumulative exposure index for the Herbert River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 65 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

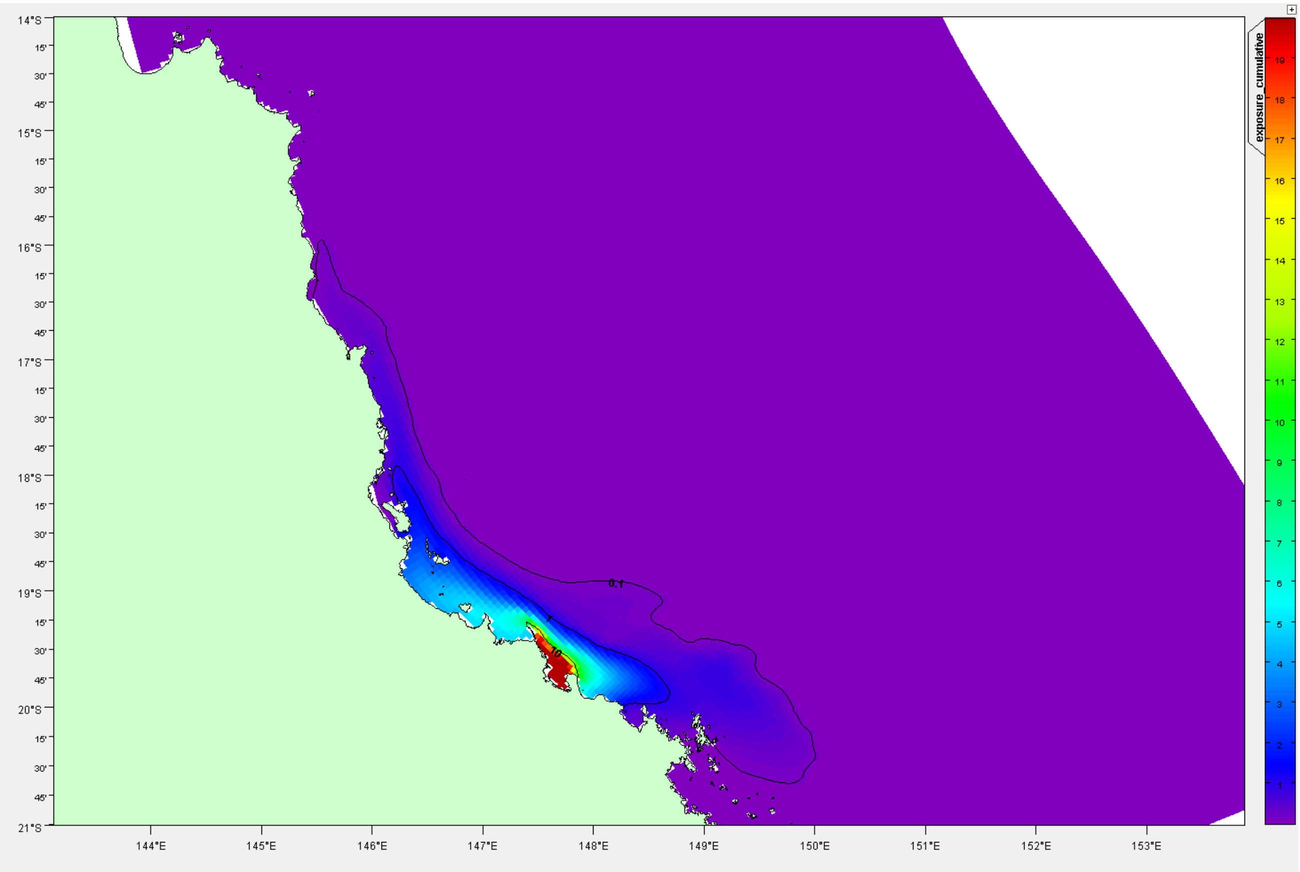

Figure A.25 Cumulative exposure index for the Burdekin River over the 2008-2009 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 95 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

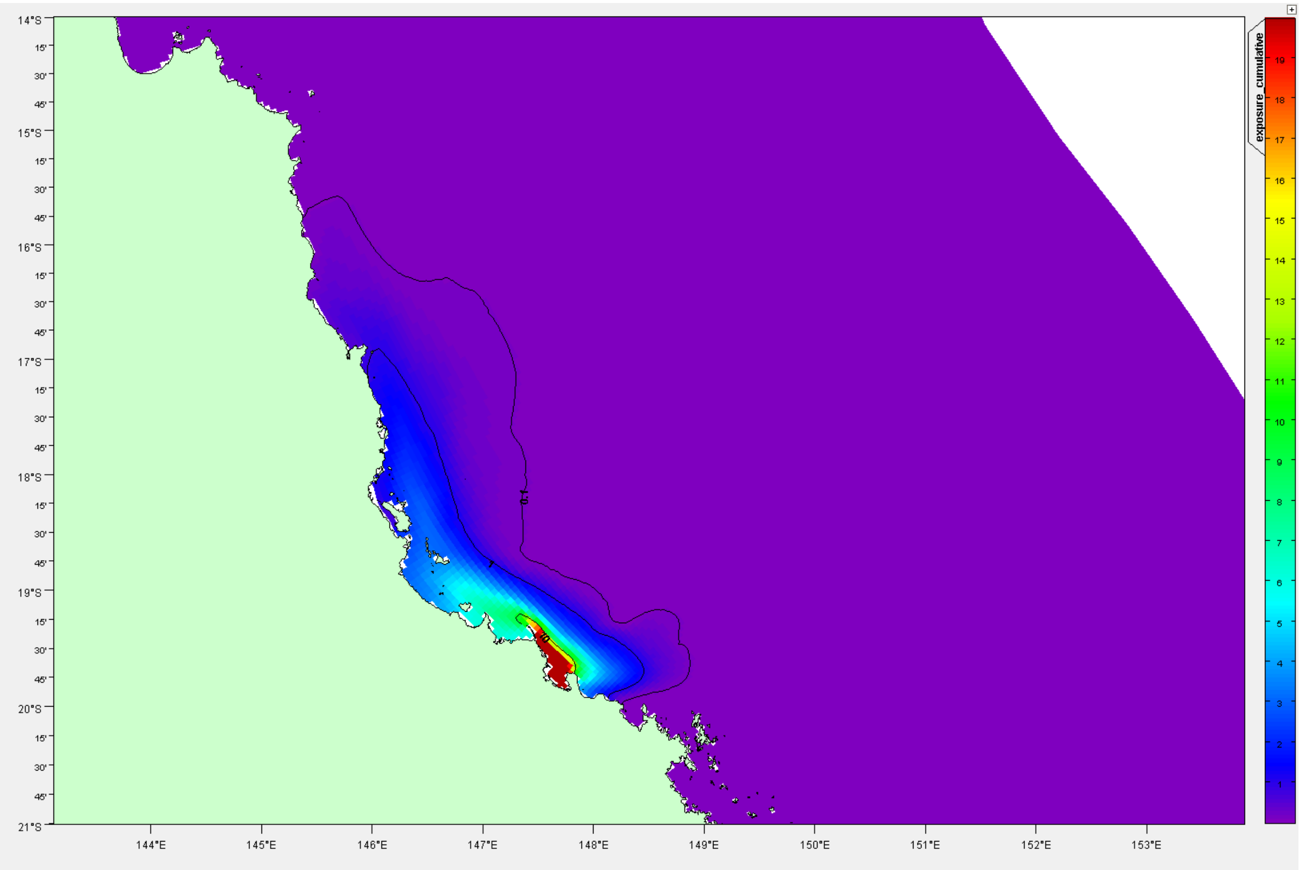

Figure A.26 Cumulative exposure index for the Burdekin River over the 2010-2011 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 116 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

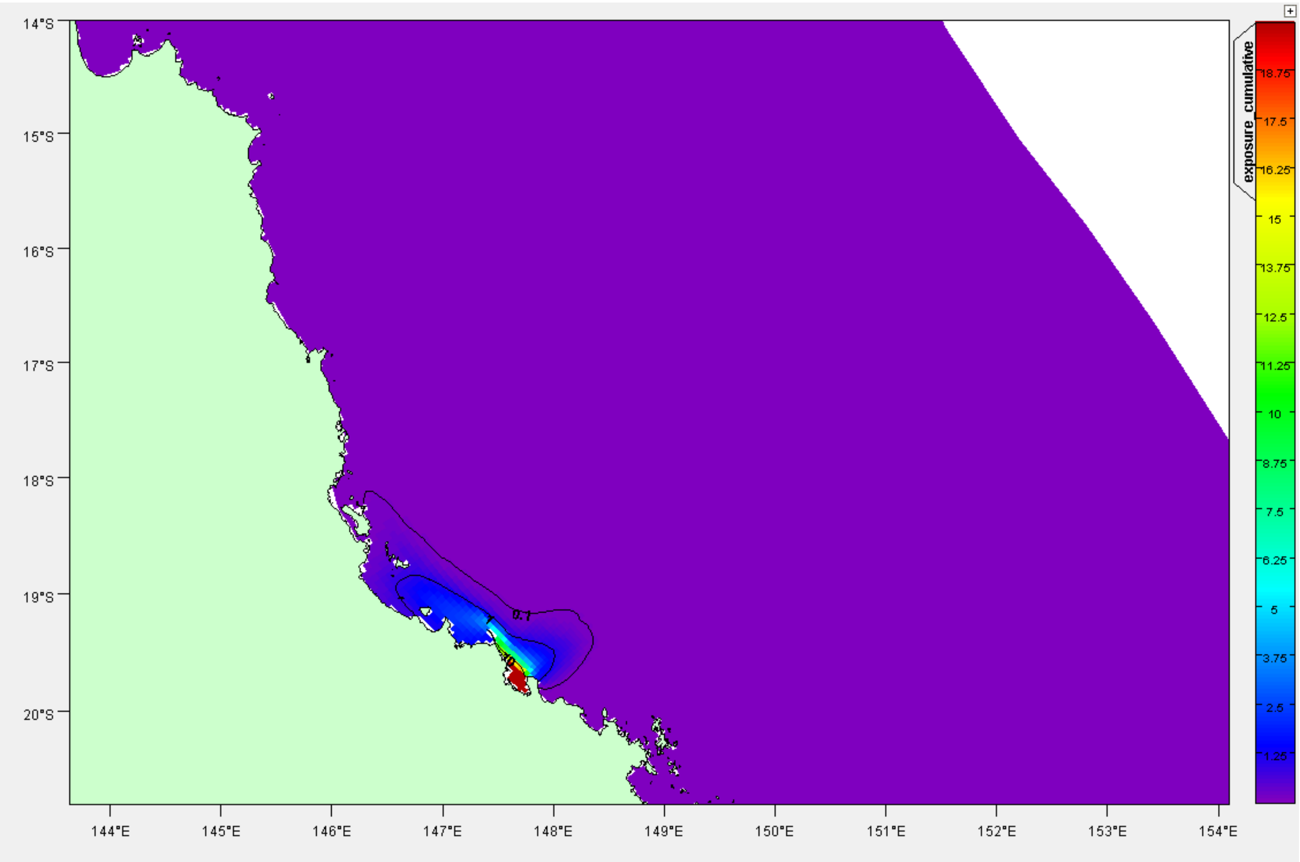

Figure A.27 Cumulative exposure index for the Burdekin River over the 2011-2012 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 82 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.

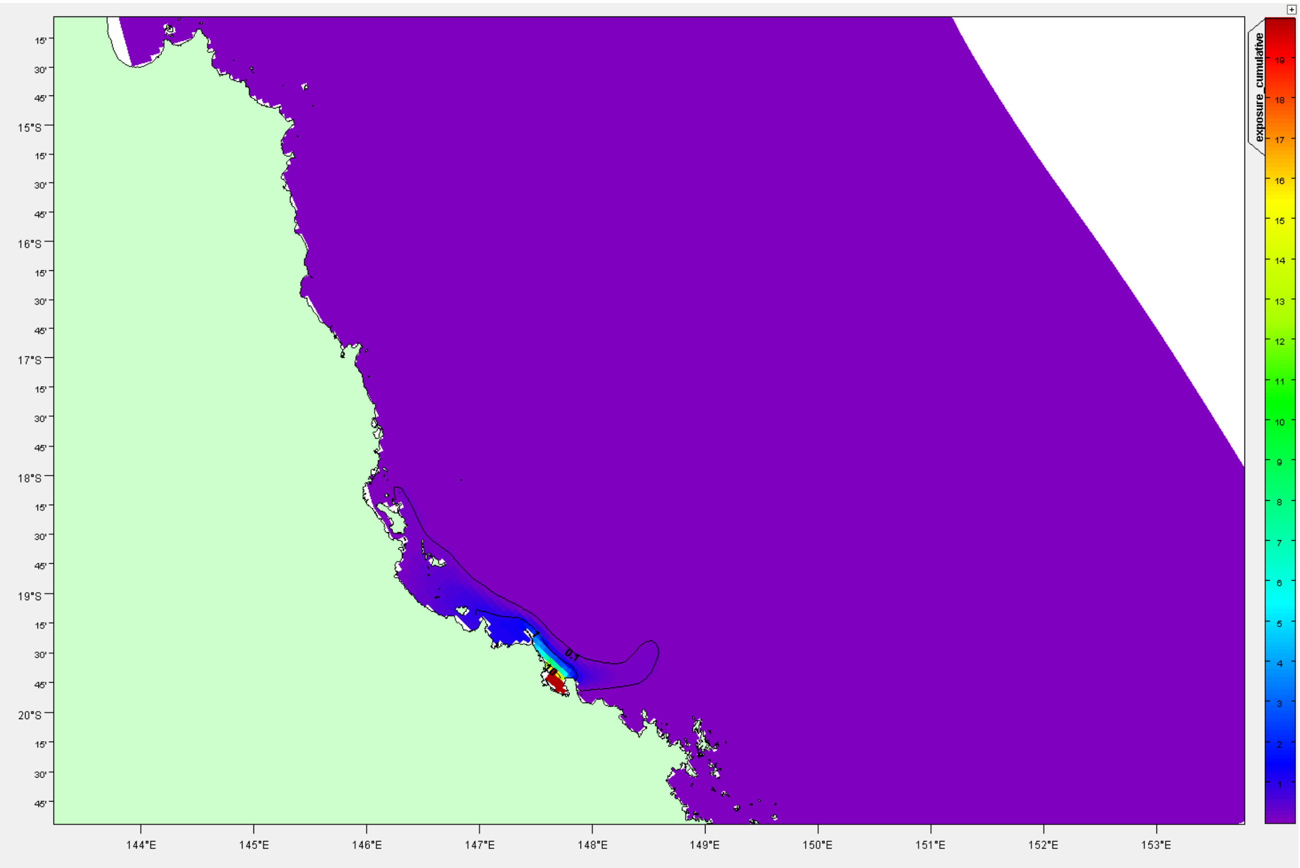

Figure A.28 Cumulative exposure index for the Burdekin River over the 2012-2013 wet seasons. The colour bar indicates the calculated cumulative exposure (concentration x days) above 1% of the incoming concentration. The colour bar is capped at 20 Conc.Days. Maximum exposure is 67 at the river mouth. Contours show 0.1, 1.0 and 10.0 Conc.Days exposure levels.